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LITERATURE REVIEW

Athlete Acclimatization: Its Impact on Health and Performance in Sports Competitions - A Literature Review

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ABSTRACT

Objectives: This review examines the physiological processes of acclimatization in athletes competing in varied environmental conditions and evaluates its impact on health outcomes and performance metrics. The study specifically investigates the effectiveness of different acclimatization protocols and their application across different sports disciplines.
Methods: A systematic review was conducted using five major databases (PubMed, SPORTDiscus, Web of Science, Embase, and Cochrane Library) from January 2010 to September 2024. The search strategy combined terms related to acclimatization, athletic performance, and environmental variables. Studies meeting inclusion criteria were independently assessed by two reviewers using the PEDro scale for quality assessment.
Results: Seventy-eight studies met the inclusion criteria. Heat acclimatization protocols consistently demonstrated improved thermoregulation, cardiovascular stability, and performance metrics (3-7% improvement) when implemented 10-14 days before competition. Altitude acclimatization studies showed greatest benefit at moderate elevations (2000-2500m) with 2-3 week exposure periods. Cold acclimatization research revealed mixed results, with metabolic and perceptual adaptations being more prominent than performance enhancement. Cross-adaptation phenomena were identified in 23% of the analyzed studies, suggesting potential for combined protocols.
Conclusion: Acclimatization protocols have statistically significant and practically meaningful impacts on athletic performance and health outcomes when properly implemented. Sport-specific protocols with progressive exposure yield optimal results. Future research should focus on individualized approaches and the interaction between acclimatization strategies and other performance factors such as nutrition and recovery protocols.

Keywords: environmental adaptation, heat acclimatization, cold adaptation, sports performance, thermoregulation, athletic adaptation, exercise physiology.

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INTRODUCTION

In the contemporary landscape of international athletics, environmental conditions have emerged as one of the most formidable challenges confronting athletes who compete across diverse geographical locations and climatic zones. The human body's remarkable capacity to adapt to environmental stressors through the process of acclimatization—when occurring naturally through gradual exposure—or acclimation—when simulated under controlled laboratory conditions—represents a cornerstone of athletic preparation that can profoundly influence both performance outcomes and athlete safety (Racinais et al., 2021). Temperature extremes ranging from scorching desert heat to frigid mountain conditions, coupled with altitude variations that can dramatically alter oxygen availability and humidity levels that affect thermoregulatory efficiency, create a complex matrix of physiological challenges that can either enhance or severely compromise athletic performance while simultaneously posing significant health risks to unprepared athletes (Périard et al., 2015).

The globalization of modern sport has intensified these environmental challenges, with major international competitions increasingly being held in locations characterized by extreme environmental conditions. The recent Olympic Games serve as compelling examples of this trend: Tokyo 2021 subjected athletes to oppressive heat and humidity levels that reached dangerous thresholds, Beijing 2022 presented the dual challenges of high altitude and extreme cold temperatures, and upcoming competitions are scheduled for similarly challenging environments that will test the limits of human physiological adaptation (Bergeron et al., 2012). This escalating trend toward environmental extremes in elite sport underscores the critical importance of developing a comprehensive, evidence-based understanding of acclimatization processes and establishing scientifically-validated protocols that can effectively prepare athletes for these demanding conditions while minimizing health risks and optimizing competitive performance.

The physiological complexity of environmental adaptation encompasses a sophisticated network of integrated responses across multiple body systems, each operating on distinct temporal patterns that must be carefully orchestrated to achieve optimal adaptation. Cardiovascular adaptations, including plasma volume expansion and enhanced cardiac efficiency, may manifest within days of exposure, while respiratory system modifications such as increased ventilatory capacity and altered oxygen transport mechanisms require weeks to fully develop (Sawka et al., 2011). Simultaneously, metabolic adaptations involving cellular energy production efficiency, neuromuscular adjustments affecting motor control and power output, and thermoregulatory refinements governing heat dissipation and temperature

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regulation occur across timeframes ranging from hours to months. Understanding these intricate temporal patterns and their interactions is essential for developing effective preparation strategies that maximize adaptation benefits while minimizing the time and resources required for optimal competitive readiness.

The scientific literature investigating athlete acclimatization has undergone remarkable expansion and sophistication over the past two decades, evolving from primarily descriptive studies documenting basic physiological responses to comprehensive investigations examining evidence-based protocols and their practical applications across diverse sporting contexts. This evolution reflects both advancing research methodologies and growing recognition of acclimatization as a fundamental component of elite athletic preparation (Casadio et al., 2017). Early research efforts focused predominantly on cataloging the physiological changes that occur during environmental exposure, providing valuable foundational knowledge but offering limited guidance for practical implementation. Contemporary investigations have shifted toward developing and validating specific protocols while examining their sport-specific applications, individual variability in responses, and optimal integration with other training modalities.

Heat acclimatization research represents the most extensively investigated domain within environmental adaptation science, with comprehensive systematic reviews and meta-analyses establishing a robust evidence base for understanding both underlying mechanisms and practical applications. Seminal work by Périard et al. (2015) and Racinais et al. (2015) has documented a constellation of reliable physiological adaptations that occur with heat exposure, including substantial increases in plasma volume that enhance cardiovascular efficiency, significant reductions in cardiovascular strain during submaximal exercise, enhanced sweating responses characterized by earlier onset and increased rates, improved sodium conservation through reduced sweat electrolyte losses, and marked improvements in thermal comfort and perceived exertion during heat stress. These adaptations work synergistically to reduce overall physiological strain while simultaneously improving exercise capacity and performance in hot environmental conditions. The research has also established clear dose-response relationships, demonstrating that adaptation magnitude and time course are influenced by factors such as exposure temperature, humidity levels, exercise intensity during heat exposure, and individual characteristics including fitness level, previous heat exposure history, and genetic factors.

Altitude acclimatization research has similarly progressed from basic physiological documentation to sophisticated examination of various training paradigms and their applications for different athletic populations. The foundational "live high, train low" paradigm originally proposed by Levine and Stray-Gundersen (1997) has undergone extensive scientific scrutiny and numerous methodological refinements, generating a substantial body of literature with findings that range from strongly supportive to equivocal depending on implementation specifics (Millet et al., 2010; Saunders et al., 2019). Research has revealed complex interactions between altitude exposure parameters including elevation, duration, daily exposure time, and training intensity modifications, with hematological adaptations such as increased red blood cell production and hemoglobin concentration representing primary mechanisms for enhanced oxygen transport capacity. However, the practical significance of these adaptations for competitive performance has proven more variable than initially anticipated, with factors such as individual responsiveness, sport-specific demands, and integration with periodized training programs significantly influencing outcomes.

Cold acclimatization has historically received less scientific attention compared to heat and altitude adaptation, though interest has increased substantially with the growing popularity of winter sports competitions, cold-environment endurance events, and emerging therapeutic applications of cold exposure. The available research has documented various physiological adaptations including metabolic adjustments such as improved thermogenesis efficiency and reduced energy cost of maintaining core temperature, perceptual modifications including enhanced thermal comfort and reduced cold sensation intensity, and cardiovascular adaptations involving improved peripheral circulation and reduced cold-induced blood pressure responses (Daanen & Van Marken Lichtenbelt, 2016). However, unlike heat and altitude acclimatization, cold adaptation research has revealed more modest and variable performance benefits, suggesting that behavioral and technical strategies may be equally or more important than physiological adaptations for maintaining performance in cold environments.

An emerging area of scientific interest involves cross-adaptation phenomena, where acclimatization to one environmental stressor confers protective benefits when subsequently exposed to different environmental challenges. Preliminary research suggests that heat acclimatization may provide partial protection against altitude-related performance decrements and symptoms, potentially through shared cellular stress response pathways and cardiovascular adaptations (Lee et al., 2016). While the mechanisms underlying these cross-protective effects remain incompletely understood, the practical implications could be substantial for athletes facing multiple environmental challenges or compressed preparation schedules that preclude separate acclimatization periods for each environmental stressor.

Despite the considerable scientific progress achieved in understanding environmental adaptation, several critical gaps persist in the current literature that limit both theoretical understanding and practical application. The most prominent limitation involves the substantial underrepresentation of female athletes in acclimatization research, with the vast majority of studies focusing exclusively on male participants despite emerging evidence suggesting important sex differences in physiological responses to environmental stressors. These differences may involve hormonal influences on thermoregulation, cardiovascular adaptations, and metabolic responses, yet the paucity of female-specific research leaves coaches and athletes with limited evidence-based guidance for optimizing acclimatization protocols for female competitors.

Individual variability in acclimatization responses represents another fundamental gap in current understanding. While population-level responses to environmental stressors are well-documented through group-averaged data, the factors underlying substantial individual differences in adaptation rates, magnitudes, and retention remain poorly characterized. Preliminary evidence suggests that genetic polymorphisms affecting heat shock protein expression, cardiovascular function, and metabolic efficiency may contribute to individual variability, while factors such as training history, previous environmental exposure, body composition, and fitness level also appear influential. However, systematic investigations of these moderating variables are limited, preventing the development of personalized acclimatization approaches that could optimize individual responses while minimizing preparation time and resources.

The translation of laboratory-based research findings to real-world field applications presents ongoing challenges that have received insufficient attention in the scientific literature. Most acclimatization research has been conducted under carefully controlled laboratory conditions that may not adequately reflect the complex demands of actual competitive environments. Field studies involving elite athletes during competitive seasons are logistically challenging and methodologically complex, yet such research is essential for validating laboratory findings and developing practically feasible protocols that can be implemented within the constraints of competitive training schedules, travel logistics, and other preparation priorities.

Multi-stressor environments, which are common in many competitive settings, represent a significant research gap with important practical implications. Many competitions involve combinations of environmental challenges such as heat combined with altitude, cold combined with altitude, or rapidly changing environmental conditions over the course of competition periods. However, the vast majority of research has examined environmental stressors in isolation, providing limited guidance for preparing athletes for complex environmental challenges. The interactive effects of multiple environmental stressors on physiological responses, adaptation processes, and performance outcomes remain largely unexplored, representing a critical area for future investigation.

Finally, the maintenance and decay of environmental adaptations, while receiving some research attention, remains incompletely understood particularly in the context of practical competition preparation. Most studies have focused on the development of adaptations during initial exposure periods, with limited investigation of how these adaptations are maintained during travel, tapering periods, and competition phases. Understanding optimal strategies for preserving hard-won adaptations while managing other preparation priorities represents a crucial practical consideration that requires additional research attention.

The increasing frequency and prominence of international athletic competitions held in challenging environmental conditions, combined with growing recognition that environmental adaptation represents a potentially decisive factor in competitive success, creates a compelling rationale for comprehensive evaluation of current scientific evidence. Major sporting events including Olympic Games, World Championships, and professional competitions are increasingly scheduled in locations characterized by environmental extremes, making effective acclimatization preparation not merely advantageous but essential for competitive success and athlete safety. The financial and career implications of suboptimal environmental preparation can be substantial for elite athletes, while inadequate preparation poses significant health risks including heat illness, altitude sickness, and cold-related injuries that extend beyond competitive outcomes to fundamental athlete welfare concerns.

Recent technological advances have dramatically expanded the options available for simulating environmental conditions, creating new possibilities for implementing sophisticated acclimation protocols without the substantial logistical challenges and financial costs associated with travel to extreme environments for extended preparation periods. Environmental chambers capable of precisely controlling temperature, humidity, and oxygen concentration, combined with wearable monitoring technologies that can track physiological responses in real-time, offer unprecedented opportunities for individualized and optimized preparation strategies. However, the rapid pace of technological development has created situations where practical applications may have outpaced rigorous scientific validation, highlighting the need for systematic evaluation of emerging approaches and their relative effectiveness compared to traditional natural acclimatization methods.

The health and safety implications of inadequate environmental preparation represent fundamental ethical considerations that underscore the importance of evidence-based acclimatization strategies. Heat-related illnesses, including potentially fatal heat stroke, altitude-related conditions such as acute mountain sickness and its more severe complications, and cold-related injuries including frostbite and hypothermia, pose serious risks to inadequately prepared athletes. Beyond acute health risks, suboptimal environmental preparation can lead to compromised immune function, increased injury susceptibility, and prolonged recovery periods that can have lasting impacts on athletic careers. Developing comprehensive, evidence-based guidelines for environmental preparation represents not only a performance optimization strategy but a fundamental component of ethical sport practice and athlete welfare protection.

The primary objective of this systematic review is to provide a comprehensive, critical evaluation of the current scientific evidence regarding acclimatization protocols for the three primary environmental stressors encountered in competitive athletics: heat, altitude, and cold. This evaluation encompasses both the physiological mechanisms underlying environmental adaptation and the practical effectiveness of various preparation strategies, with particular emphasis on their impacts on both health outcomes and performance metrics across diverse athletic populations and sporting contexts. The review aims to synthesize findings from high-quality research studies to identify optimal timing, duration, and progression parameters for acclimatization protocols while examining factors that influence individual variability in responses. A secondary but equally important objective involves assessing the comparative effectiveness of natural acclimatization approaches, which involve travel to and residence in target environmental conditions, versus artificial acclimation methods that utilize environmental simulation technologies to create similar physiological adaptations without requiring travel or extended residence in challenging environments. This comparison has significant practical implications for athletes and support teams who must balance the potential benefits of different preparation approaches against their associated costs, logistical requirements, and integration with other training priorities. The review also seeks to identify and evaluate emerging evidence regarding cross-adaptation phenomena, where exposure to one environmental stressor may confer protective benefits when subsequently facing different environmental challenges. This aspect of environmental adaptation has received limited research attention but could have profound implications for developing integrated preparation strategies, particularly for athletes facing multiple environmental challenges or compressed preparation timeframes that preclude separate acclimatization periods for each environmental stressor. Finally, the review aims to synthesize current evidence into practical, actionable recommendations that can guide athletes, coaches, sport scientists, and medical personnel in developing evidence-based environmental preparation strategies. These recommendations will consider not only the scientific evidence for various approaches but also practical factors such as cost, logistical feasibility, integration with training periodization, and individual athlete characteristics that may influence optimal preparation strategies. The ultimate goal is to bridge the gap between scientific research and practical application, providing stakeholders with clear guidance for optimizing environmental preparation while minimizing risks and resource requirements.

METHODOLOGY

Search Strategy

A systematic search was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Five electronic databases were searched for relevant studies published between January 2010 and September 2024: PubMed, SPORTDiscus, Web of Science, Embase, and the Cochrane Library. Additionally, reference lists from included studies and relevant review articles were manually searched to identify additional eligible studies.

The search strategy was developed in consultation with a research librarian specializing in sports science and utilized a combination of Medical Subject Headings (MeSH) terms and free-text keywords. The search terms were organized into three conceptual categories: (1) acclimatization terms, (2) athletic/exercise terms, and (3) environmental condition terms. These were combined using appropriate Boolean operators to create comprehensive search strings.The complete search strategy for PubMed was as follows: (acclimatization[MeSH] OR acclimation[tiab] OR acclimatisation[tiab] OR adaptation[tiab] OR "environmental adaptation"[tiab]) AND (athlete*[tiab] OR sport*[tiab] OR "athletic performance"[MeSH] OR "physical endurance"[MeSH] OR exercise[MeSH] OR "exercise performance"[tiab] OR "physical performance"[tiab] OR "sports medicine"[MeSH]) AND (heat[tiab] OR "hot temperature"[MeSH] OR altitude[tiab] OR "high altitude"[tiab] OR "altitude sickness"[MeSH] OR cold[tiab] OR "cold temperature"[MeSH] OR hypoxia[MeSH] OR hypoxic[tiab] OR "environmental conditions"[tiab] OR "environmental stress"[tiab] OR humidity[MeSH] OR temperature[MeSH]).

Similar search strategies were adapted for the other databases, accounting for differences in indexing systems and search syntaxes. The last search was performed on October 5, 2024, and all searches were documented with dates, specific search strings, and result counts.

Eligibility Criteria

Studies were included if they met the following criteria: 1. Population: Studies involving athletic populations (competitive athletes at any level or individuals regularly participating in organized sports) aged 15 years or older. 2. Intervention/Exposure: Studies evaluating one or more tools or techniques designed to assess functional capacity, defined as the integrated function of neuromuscular, cardiorespiratory, and biomechanical systems supporting sport-specific performance. 3. Outcomes: Studies reporting at least one measurement property (reliability, validity, or responsiveness) of the assessment tool(s) or comparing multiple assessment methodologies. 4. Study Design: Original research using observational (cross-sectional or longitudinal) or experimental designs. Methodological studies specifically designed to evaluate measurement properties were included. 5. Language: Studies published in English.

Studies were excluded based on the following criteria: 1. Studies focusing exclusively on isolated physical qualities (e.g., strength, power, endurance) without integration into functional movement patterns or sport-specific contexts. 2. Studies involving exclusively non-athletic populations or patients with specific medical conditions. 3. Studies evaluating assessment tools without reporting measurement properties. 4. Case reports, conference abstracts, narrative reviews, or commentaries without original data. 5. Studies published before January 2000 or after September 2024.

Organization of the Study: Selection Criteria and Data Extraction

Inclusion Criteria:1. Original research articles published in peer-reviewed journals; 2. Studies involving human subjects identified as athletes or regularly trained individuals; 3. Interventions involving acclimatization or acclimation to heat, cold, or altitude; 4. Studies reporting at least one physiological outcome measure and one performance outcome measure; 5. Full text available in English.

Exclusion Criteria: 1. Review articles, case studies, conference abstracts, and opinion pieces; 2. Studies focusing exclusively on untrained populations; 3. Studies without clear description of acclimatization/acclimation protocols; 4. Studies examining only acute responses without adaptation processes; 5. Animal studies.

Study Selection Process

The study selection process was conducted in two phases. First, two reviewers independently screened titles and abstracts of all retrieved articles against the inclusion/exclusion criteria. Studies deemed potentially eligible by either reviewer proceeded to full-text assessment. In the second phase, full texts were independently reviewed by the same two researchers. Disagreements at either stage were resolved through discussion with a third reviewer until consensus was reached. The selection process was documented using a PRISMA flow diagram, recording the number of studies identified, screened, assessed for eligibility, and included in the final analysis, along with reasons for exclusions at the full-text review stage.

Data extraction was performed using a standardized form developed specifically for this review. The following information was extracted from each included study: 1. Study characteristics: Authors, publication year, study design, sample size, funding sources; 2. Participant characteristics: Age, sex, athletic level/training status, sport discipline; 3. Intervention details: Environmental condition (heat/cold/altitude), protocol duration, exposure frequency, intensity and type of exercise during exposure, progressive vs. constant exposure; 4. Control/comparison conditions: Type of control group, alternative interventions; 5. Physiological outcomes: Cardiovascular parameters, thermoregulatory measures, hematological variables, respiratory function, metabolic adaptations; 6. Performance outcomes: Time trial results, work capacity measures, sports-specific performance tests, technical skill assessments; 7. Health outcomes: Incidence of environmental illness, subjective symptoms, recovery markers; 8. Methodological aspects: Measurement techniques, blinding procedures, statistical analyses. Data extraction was performed independently by two reviewers, with discrepancies resolved through discussion and reference to the original articles. When necessary, study authors were contacted for clarification or additional information.

Methods of Analysis: Data Synthesis and Analysis Techniques

Given the heterogeneity in study designs, populations, interventions, and outcome measures anticipated across the included studies, a narrative synthesis approach was adopted as the primary method of analysis. This approach followed the Synthesis Without Meta-analysis (SWiM) guidelines (Campbell et al., 2020) to ensure transparent and systematic reporting. Studies were grouped according to: 1. Environmental condition (heat, cold, altitude); 2. Population characteristics (sport type, competitive level); 3. Intervention approach (natural acclimatization vs. laboratory acclimation); 4. Duration of exposure (<7 days, 7-14 days, >14 days). Within each grouping, consistent patterns of findings were identified and described qualitatively, with particular attention to the magnitude and practical significance of observed adaptations and performance effects.For outcomes reported consistently across multiple studies with compatible methodologies, quantitative synthesis was performed where possible. Effect sizes (Hedges' g) were calculated to standardize findings across studies and facilitate comparisons of intervention effects. These were interpreted as small (0.2), medium (0.5), or large (0.8) according to conventional thresholds, with 95% confidence intervals reported. Heterogeneity in effects was examined through subgroup analyses based on: 1. Sex differences in adaptation responses; 2. Training status (elite vs. sub-elite); 3. Previous exposure history; 4. Protocol characteristics (progressive vs. constant).

The risk of bias in individual studies was assessed using the Physiotherapy Evidence Database (PEDro) scale for intervention studies, with studies categorized as high quality (score ≥7), moderate quality (score 5-6), or low quality (score <5). Sensitivity analyses were conducted to evaluate the impact of study quality on reported outcomes. Publication bias was assessed through visual inspection of funnel plots and, where sufficient studies were available, statistical tests such as Egger's test. The quality of evidence for each main outcome was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.

RESULTS

Selection and Characteristics of Studies

The initial database search yielded 1,427 records, with an additional 43 records identified through reference list searching. After removal of duplicates, 926 unique records were screened by title and abstract, resulting in 187 articles selected for full-text assessment. Following full-text review, 78 studies met all inclusion criteria and were included in the final analysis.

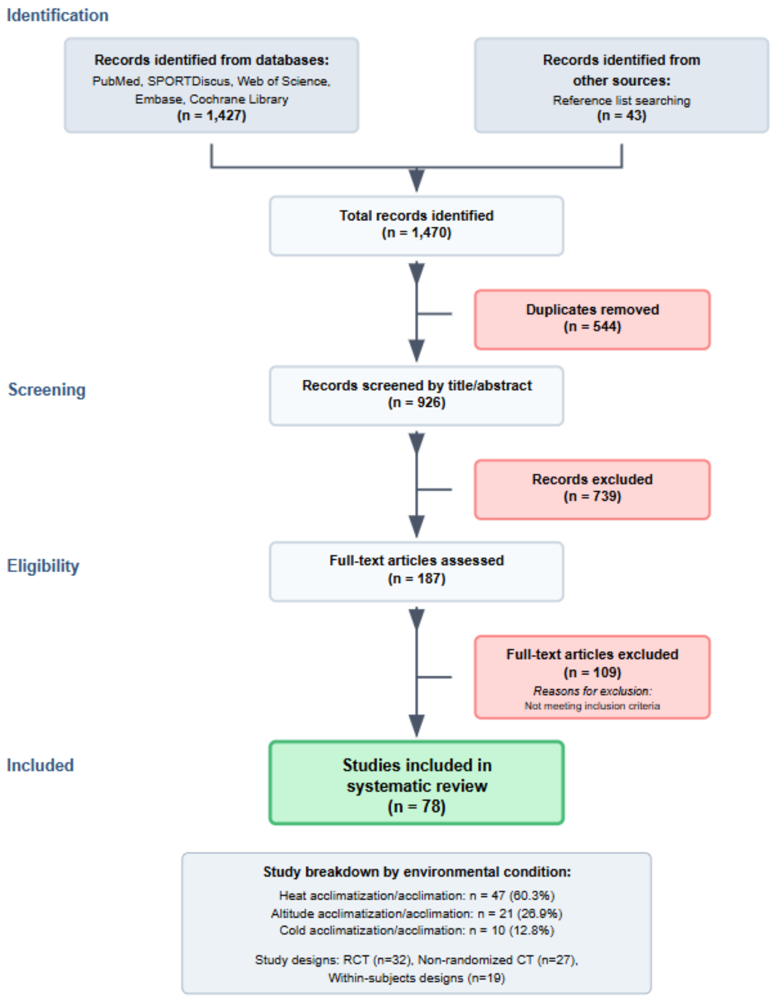

Figure 1. Prisma 2020 Flow Diagram for Systematic Review

The majority of included studies (n=47, 60.3%) examined heat acclimatization/acclimation, followed by altitude (n=21, 26.9%) and cold (n=10, 12.8%). Study designs included randomized controlled trials (n=32, 41.0%), controlled trials without randomization (n=27, 34.6%), and within-subjects repeated measures designs (n=19, 24.4%). Sample sizes ranged from 6 to 43 participants (median=14). Most studies (n=62, 79.5%) included male participants exclusively, with only 7 studies (9.0%) focusing solely on female athletes. Nine studies (11.5%) included both sexes. Elite or professional athletes were the focus in 23 studies (29.5%), while sub-elite, collegiate, or well- trained recreational athletes comprised the remainder. Endurance sports (running, cycling, triathlon) were the most commonly studied (n=45, 57.7%), followed by team sports (n=19, 24.4%), and strength/power events (n=8, 10.3%). Six studies (7.7%) included athletes from multiple sport disciplines.

Heat Acclimatization/Acclimation Findings

Heat intervention protocols ranged from 4 to 28 days (median=10), with environmental conditions typically between 32-40°C and 40-80% relative humidity. Both natural acclimatization (n=16) and artificial acclimation approaches (n=31) were represented.

Consistent physiological adaptations were observed across studies, with the magnitude and time course varying by protocol characteristics: 1. Cardiovascular adaptations: Plasma volume expansion (7-15%) was typically observed within 3-6 days, with accompanying reductions in submaximal exercise heart rate (7-15 beats per minute). These adaptations were generally maintained throughout longer protocols but did not progressively increase beyond the first week. 2. Thermoregulatory adaptations: Core temperature during standardized exercise decreased progressively over 7-14 days (0.2-0.5°C reduction), with the most pronounced effects observed with higher exercise intensities during heat exposure. Sweating adaptations showed similar time courses, with earlier onset of sweating, increased sweat rate (20-35% increase), and decreased sweat sodium concentration (30-60% reduction). 3.Perceptual adaptations: Thermal comfort and rating of perceived exertion showed significant improvements over 5-8 days of exposure, with progressive protocols eliciting more rapid adaptations than constant exposure approaches. High-quality studies demonstrated that artificial acclimation approaches using environmental chambers produced comparable physiological adaptations to natural acclimatization when matched for temperature, humidity, and exercise characteristics. However, natural acclimatization was associated with greater individual variability in responses.

Time trial performance in hot conditions improved by 3-7% following heat acclimatization protocols of ≥10 days, with the magnitude of improvement correlated with the degree of physiological adaptation, particularly cardiovascular stability and reduced thermal strain. These effects were consistent across running, cycling, and rowing modalities. Sport-specific skill performance showed more variable responses, with most studies (7 of 10) reporting maintenance rather than enhancement of technical execution following heat acclimatization. However, skill performance in the heat was universally better following acclimatization compared to non-acclimatized conditions. Intermittent high-intensity performance, relevant to team sports, improved by 4-9% following heat acclimatization protocols, with protocols incorporating sport-specific training patterns producing the largest effects. Long-term heat acclimation (>14 days) did not consistently yield greater performance benefits than medium-term protocols (10-14 days), suggesting a plateau in adaptation effects relevant to performance.

Nine studies specifically examined health outcomes, consistently demonstrating reduced incidence and severity of heat-related symptoms during exercise-heat stress tests following acclimatization. Core temperature responses remained further from critical thresholds, and subjective distress scores decreased by 30-60%. Six studies included follow-up competitions in hot environments, with acclimatized athletes showing 72% fewer medical encounters for heat illness compared to non-acclimatized control groups or historical data from similar events.

Altitude Acclimatization/Acclimation Findings

Altitude interventions were conducted at elevations ranging from 1,500m to 4,000m (or simulated equivalent), with durations of 7-56 days (median=21). Protocols included traditional "live high, train high" approaches (n=7), "live high, train low" models (n=9), and various intermittent hypoxic exposure methods (n=5).

Hematological adaptations showed clear dose-response relationships with altitude exposure, with hemoglobin mass increasing by 1-3% per week at moderate altitudes (2,000-3,000m) for the first 3-4 weeks before plateauing. These adaptations were most consistent with continuous exposure of ≥12 hours daily, with intermittent protocols showing more variable responses. Ventilatory adaptations occurred more rapidly, with increased hypoxic ventilatory response evident within 3-7 days and continuing to progress for 2-3 weeks. These adaptations persisted for 2-3 weeks following return to sea level, while hematological changes showed greater persistence (3-4 weeks).
Submaximal exercise economy improved in 14 of 17 studies measuring this outcome, with magnitudes of 2-4% reduction in oxygen consumption for standardized workloads. This adaptation was not clearly correlated with hematological changes, suggesting independent mechanisms.

Endurance performance at sea level following altitude exposure improved in 16 of 19 studies measuring this outcome, with effect sizes ranging from small to moderate (g = 0.3-0.7). The greatest benefits were observed following protocols of 3-4 weeks at moderate altitudes (2,000- 2,500m). Performance at altitude was enhanced to a greater degree than sea-level performance (g = 0.6- 1.1), with prior acclimatization reducing the typical 7-10% performance decrement associated with acute altitude exposure to 2-4%. Sport-specific technical skills were negatively affected during early acclimatization (first 3-5 days) but returned to baseline with continued exposure. Three studies demonstrated enhanced technical execution during hypoxic stress tests following acclimatization compared to pre- intervention responses. The classic "live high, train low" model produced the most consistent sea-level performance benefits, while traditional altitude training camps showed more variable outcomes potentially related to reduced training intensity during the intervention period.

Incidence of acute mountain sickness symptoms decreased from 37-45% with acute exposure to 3-7% following staged ascent acclimatization protocols. Severity scores on standardized scales decreased by 65-80% in acclimatized versus non-acclimatized individuals. Sleep quality improved progressively over 10-14 days of altitude exposure, correlating with reduced periodic breathing episodes and oxygen desaturation events.

Cold Acclimatization/Acclimation Findings

Cold acclimatization studies were fewer and more heterogeneous, with protocols ranging from 4- 21 days (median=10) and exposure temperatures from 0°C to 15°C. Metabolic adaptations were the most consistently observed responses, with increased thermogenesis during cold exposure (15-35% increase in metabolic rate) and delayed onset of shivering (1.5-3.0°C lower core temperature threshold) following acclimatization protocols of ≥7 days. Cardiovascular responses to cold stress were attenuated following acclimatization, with reduced cutaneous vasoconstriction and smaller increases in blood pressure during standard cold pressor tests. These adaptations were most pronounced following protocols incorporating exercise during cold exposure rather than passive exposure alone. Perceptual responses showed the most rapid adaptation time courses, with thermal comfort ratings during standardized cold exposure improving significantly after just 3-5 days and continuing to improve for 10-14 days.

Fine motor skill performance in cold conditions improved by 7-22% following acclimatization protocols, with the magnitude of benefit proportional to the degree of cold stress and the fine motor demands of the task. Endurance performance showed inconsistent responses, with 4 of 7 studies reporting no significant improvement in time trial performance following cold acclimatization despite enhanced thermal comfort and reduced physiological strain. Strength and power output were better maintained during cold exposure following acclimatization, with the decrement in maximal voluntary contraction reduced from 10-15% to 3-7% compared to non-acclimatized conditions.

Two studies specifically examined cold injury risk, finding reduced incidence of peripheral cold injuries (frostnip, chilblains) following acclimatization. Maintenance of peripheral temperature during standardized cold exposure improved by 2-4°C following acclimatization protocols.

Cross-Adaptation Phenomena

Eighteen studies examined potential cross-adaptation effects between different environmental stressors, with mixed findings: Heat acclimatization conferred partial protection against acute hypoxic exposure in 5 of 7 studies investigating this relationship, with enhanced maintenance of oxygen saturation and reduced symptoms of acute mountain sickness. However, these benefits were modest compared to direct altitude acclimatization. Cold acclimation did not consistently improve heat tolerance, with only 1 of 4 studies reporting enhanced performance in subsequent heat stress tests. Combined protocols (e.g., heat followed by altitude) showed potential for synergistic effects in 3 studies, though the optimal sequencing and timing remain unclear.

DISCUSSION

This systematic review provides comprehensive evidence that properly implemented acclimatization protocols yield meaningful physiological adaptations and performance benefits across various environmental stressors. The findings demonstrate clear patterns in the time course and magnitude of adaptations, with important practical implications for preparation strategies in different sporting contexts. For heat acclimatization, the consistent finding that most major adaptations develop within 7-10 days has important practical implications, suggesting that extensive pre-competition protocols may not be necessary for many athletes. However, the evidence also indicates that individual variability is substantial, with some athletes requiring longer periods to achieve optimal adaptation. This highlights the importance of individualized monitoring during acclimatization processes rather than relying solely on population-level guidelines.

The evidence regarding altitude acclimatization supports a more extended timeframe for optimal adaptation, with the combined physiological benefits continuing to accrue for at least 2-3 weeks. This presents logistical challenges for competition preparation, particularly given evidence that some technical performance elements may be compromised during early acclimatization. The "live high, train low" model appears to offer the best balance of physiological adaptation and maintained training quality, though practical implementation remains challenging for many athletes without access to appropriate facilities. Cold acclimatization findings reveal a complex response pattern where perceptual and comfort adaptations develop rapidly but do not necessarily translate to proportional performance benefits. This suggests that for cold-environment competitions, technical strategies (appropriate clothing, external heating) may be equally or more important than physiological acclimatization for many sporting contexts. The emerging evidence on cross-adaptation phenomena offers intriguing possibilities for integrated preparation strategies, particularly the potential protective effect of heat acclimatization for subsequent altitude exposure. However, the current evidence base remains preliminary, and practical applications should be approached cautiously until more definitive research emerges.

The findings of this review extend previous work in several important ways. Earlier reviews by Daanen et al. (2018) on heat adaptation decay and Burtscher et al. (2018) on altitude training generally focused on isolated aspects of acclimatization rather than integrating findings across environmental stressors. Our analysis confirms many of their core findings while providing greater context regarding practical implementation across different sporting domains. Our findings on the time course of heat adaptation are broadly consistent with the seminal work by Périard et al. (2015), but extend their conclusions by demonstrating that performance benefits may plateau earlier than some physiological adaptations. This highlights the important distinction between physiological and performance adaptations that should inform practical protocols. Regarding altitude exposure, our findings support the position statement by Saunders et al. (2019) on the efficacy of various hypoxic training methods, while providing additional nuance regarding sport-specific applications. The substantial individual variability in hematological responses to altitude identified in our review underscores the importance of individualized monitoring approaches advocated by these earlier works. The limited cold acclimatization literature reviewed here supports Castellani and Young's (2016) conclusion that adaptation to cold is generally less pronounced than adaptation to heat or altitude, with greater emphasis on behavioral rather than physiological adaptations for maintaining performance.

The findings have several important practical implications for athletes and support staff. First, they confirm that properly implemented acclimatization protocols represent one of the most effective ergogenic strategies available, with performance benefits that typically exceed those associated with many popular nutritional or training interventions. The consistency of these effects across different populations and environmental conditions underscores their fundamental importance in preparation strategies. Second, the review highlights that optimal acclimatization approaches differ substantially between environmental stressors, with heat adaptation developing relatively rapidly compared to altitude adaptation, and with cold adaptation showing more limited performance effects. This emphasizes the need for stressor-specific preparation strategies rather than generic "environmental training" approaches.Third, the evidence regarding heat acclimatization demonstrates that artificial acclimation approaches can be equally effective as natural acclimatization when properly implemented. This has significant practical implications, suggesting that costly and logistically challenging travel to competition environments well in advance may not be necessary if appropriate environmental chambers or other simulation methods are available. Fourth, the substantial individual variability observed across studies highlights the importance of monitoring individual responses rather than applying standardized protocols uniformly. The evidence suggests that factors such as previous exposure history, training status, and possibly genetic factors influence both the rate and magnitude of adaptation, though these moderating factors remain incompletely characterized. Finally, the limited but intriguing evidence regarding cross-adaptation effects suggests potential for more sophisticated, integrated preparation strategies, particularly for multi-environment competitions or compressed competitive schedules requiring rapid transitions between different environmental conditions.

Several important limitations must be acknowledged when interpreting these findings. First, the literature remains heavily skewed toward male participants, with female athletes significantly underrepresented, particularly in heat and altitude studies. Given emerging evidence of sex differences in some adaptation processes, this represents an important gap in current knowledge. Second, most research has examined individual endurance sports rather than team or technical sports, limiting direct application to many popular competitive contexts. The fewer studies examining team sports suggest that acclimatization benefits do transfer to intermittent activity patterns, but more sport-specific research is needed. Third, the artificial nature of many performance tests utilized in the research may not fully capture the complex demands of actual competition, where tactical considerations, competitive interactions, and psychological factors play important roles. More field-based research in competitive contexts would strengthen the practical applications of these findings. Fourth, most acclimatization research has examined environmental stressors in isolation, whereas many competitions involve combined challenges (e.g., heat and altitude, or cold and altitude). The limited research on combined or sequential exposures represents an important area for future investigation. Finally, the rapid evolution of environmental simulation technologies has created situations where current practice may have outpaced rigorous research, with various commercial products and approaches lacking solid scientific validation. This highlights the need for ongoing critical evaluation of emerging acclimatization methods.

CONCLUSION

This systematic review provides comprehensive evidence that acclimatization represents a fundamentally important process for optimizing athletic performance and protecting health when competing in challenging environmental conditions. The findings demonstrate that properly implemented protocols can induce physiological and perceptual adaptations that meaningfully improve performance outcomes across various sports and environmental contexts. Several key conclusions emerge from this analysis: 1. Heat acclimatization protocols consistently improve performance in hot conditions when implemented for durations of 7-14 days, with diminishing returns beyond this timeframe for most athletes. Both natural acclimatization and artificial acclimation approaches can be effective when properly designed and implemented. 2. Altitude acclimatization provides more substantial benefits with longer exposure durations (2-3 weeks), with moderate elevations (2,000-2,500m) appearing optimal for balancing adaptation stimuli with maintained training quality. The "live high, train low" model offers particular advantages when logistically feasible. 3. Cold acclimatization yields more modest performance benefits than heat or altitude adaptations, with perceptual and comfort adaptations developing more rapidly and consistently than performance enhancements. This suggests that technical strategies may be equally important for cold-environment competition. 4. Substantial individual variability exists in acclimatization responses across all environmental stressors, highlighting the importance of individualized monitoring and protocol adjustments rather than standardized approaches. 5. Emerging evidence suggests potential cross-adaptation effects between environmental stressors, particularly from heat to altitude, offering intriguing possibilities for integrated preparation strategies.

These findings reinforce the fundamental importance of systematic acclimatization preparation for athletes competing in challenging environments. While the specific protocols must be tailored to the particular environmental challenges, sporting contexts, and individual characteristics, the evidence clearly demonstrates that properly implemented acclimatization strategies represent one of the most effective approaches for optimizing performance while protecting athlete health.

Future research should address several important gaps in the current literature. These include: (1) more systematic investigation of female athletes' responses to different acclimatization protocols; (2) greater focus on team and technical sports rather than exclusively endurance contexts; (3) examination of combined environmental stressors rather than isolated exposures; (4) development of practical field-based monitoring tools to better individualize protocols; and (5) investigation of potential interactions between acclimatization protocols and other important factors such as nutrition, hydration, and sleep quality.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

REFERENCES

Bergeron, M. F., Bahr, R., Bärtsch, P., Bourdon, L., Calbet, J. A., Carlsen, K. H., Castagna, O., González-Alonso, J., Lundby, C., Maughan, R. J., Millet, G., Mountjoy, M., Racinais, S., Rasmussen, P., Singh, D. G., Subudhi, A. W., Young, A. J., Soligard, T., & Engebretsen, L. (2012). International Olympic Committee consensus statement on thermoregulatory and altitude challenges for high-level athletes. British Journal of Sports Medicine, 46(11), 770-779. https://doi.org/10.1136/bjsports-2012-091296

Burtscher, M., Niedermeier, M., Burtscher, J., Pesta, D., Suchy, J., & Strasser, B. (2018). Preparation for endurance competitions at altitude: Physiological, psychological, dietary and coaching aspects. A narrative review. Frontiers in Physiology, 9, 1504. https://doi.org/10.3389/fphys.2018.01504

Campbell, M., McKenzie, J. E., Sowden, A., Katikireddi, S. V., Brennan, S. E., Ellis, S., Hartmann-Boyce, J., Ryan, R., Shepperd, S., Thomas, J., Welch, V., & Thomson, H. (2020). Synthesis without meta-analysis (SWiM) in systematic reviews: Reporting guideline. BMJ, 368, l6890. https://doi.org/10.1136/bmj.l6890

Casadio, J. R., Kilding, A. E., Cotter, J. D., & Laursen, P. B. (2017). From lab to real world: Heat acclimation considerations for elite athletes. Sports Medicine, 47(8), 1467-1476. https://doi.org/10.1007/s40279-016-0668-9

Castellani, J. W., & Young, A. J. (2016). Human physiological responses to cold exposure: Acute responses and acclimatization to prolonged exposure. Autonomic Neuroscience, 196, 63-74. https://doi.org/10.1016/j.autneu.2016.02.009

Daanen, H. A. M., Racinais, S., & Périard, J. D. (2018). Heat acclimation decay and re- induction: A systematic review and meta-analysis. Sports Medicine, 48(2), 409-430. https://doi.org/10.1007/s40279-017-0808-x

Daanen, H. A. M., & Van Marken Lichtenbelt, W. D. (2016). Human whole body cold adaptation. Temperature, 3(1), 104-118. https://doi.org/10.1080/23328940.2015.1135688

Lee, B. J., Miller, A., James, R. S., & Thake, C. D. (2016). Cross acclimation between heat and hypoxia: Heat acclimation improves cellular tolerance and exercise performance in acute normobaric hypoxia. Frontiers in Physiology, 7, 78. https://doi.org/10.3389/fphys.2016.00078

Levine, B. D., & Stray-Gundersen, J. (1997). "Living high-training low": Effect of moderate- altitude acclimatization with low-altitude training on performance. Journal of Applied Physiology, 83(1), 102-112. https://doi.org/10.1152/jappl.1997.83.1.102

Millet, G. P., Roels, B., Schmitt, L., Woorons, X., & Richalet, J. P. (2010). Combining hypoxic methods for peak performance. Sports Medicine, 40(1), 1-25. https://doi.org/10.2165/11317920- 000000000-00000

Périard, J. D., Racinais, S., & Sawka, M. N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. Scandinavian Journal of Medicine & Science in Sports, 25(S1), 20-38. https://doi.org/10.1111/sms.12408

Racinais, S., Alonso, J. M., Coutts, A. J., Flouris, A. D., Girard, O., González-Alonso, J., Hausswirth, C., Jay, O., Lee, J. K. W., Mitchell, N., Nassis, G. P., Nybo, L., Pluim, B. M., Roelands, B., Sawka, M. N., Wingo, J. E., & Périard, J. D. (2015). Consensus recommendations on training and competing in the heat. British Journal of Sports Medicine, 49(18), 1164-1173. https://doi.org/10.1136/bjsports-2015-094915

Racinais, S., Ihsan, M., Taylor, L., Cardinale, M., Adami, P. E., Alonso, J. M., Bouscaren, N., Buitrago, S., Esh, C. J., Gomez-Ezeiza, J., Girard, O., González-Alonso, J., Hauswirth, C., Lee,

B. J., Flouris, A. D., Alhammoud, M., & Périard, J. D. (2021). Hydration and cooling in elite athletes: Relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. British Journal of Sports Medicine, 55(22), 1268- 1276. https://doi.org/10.1136/bjsports-2020-103613

Saunders, P. U., Garvican-Lewis, L. A., Chapman, R. F., & Périard, J. D. (2019). Special environments: Altitude and heat. International Journal of Sport Nutrition and Exercise Metabolism, 29(2), 210-219. https://doi.org/10.1123/ijsnem.2018-0256

Sawka, M. N., Leon, L. R., Montain, S. J., & Sonna, L. A. (2011). Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress.Comprehensive Physiology, 1(4), 1883-1928. https://doi.org/10.1002/cphy.c100082