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REVIEW

The Norseman Xtreme Triathlon: A narrative review of current scientific evidence on performance, physiology, and health risks

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Abstract

Background The 'Norseman Xtreme Triathlon', held annually in Norway, is considered one of the world's most challenging triathlons, surpassing the traditional IRONMAN®-distance in terms of difficulty. This narrative review aims to summarize the current scientific evidence to support athletes and coaches in preparation for this event.

Methods We conducted a narrative review to summarize the current scientific literature on the 'Norseman Xtreme Triathlon'. A structured search was conducted in two major databases—PubMed and Scopus—using free-text terms related to 'Norseman Xtreme Triathlon'. The search included articles published up to the end of November 2025, without language restrictions. After removing duplicates and unrelated articles based on title and abstract screening, 16 relevant publications were included for analysis.

Results Over the years, the number of female and male finishers increased, the men-to-women ratio decreased, and both split and overall race times decreased. Most athletes competing in the 'Norseman Xtreme Triathlon' came from Norway, and Norwegian athletes achieved the most podiums. The race affects different organ systems and biomarkers, with increased values of WBC, CK, NT-proBNP, CRP and AST returning to pre-race levels within hours or days. Due to the cold environment, athletes appeared to be at risk of developing hypothermia and swimming-induced pulmonary edema (SIPE) during swimming and both exercise-induced bronchoconstriction (EIB) and exercise-induced arterial hypoxemia (EIAH) after the race.

Conclusions Particular care is needed in preparing for the cold water and general cold environment during cycling and running. The specific nutritional demands, the aspects of pre-race preparation (*e.g.* training, experience), post-race recovery trajectories, hormonal profiles, or psychological responses of the 'Norseman Xtreme Triathlon' remain underexplored and represent an important area for future research.

Keywords Swimming · Cycling · Running · Ultra-endurance · Extreme endurance events

Introduction

The 'Norseman Xtreme Triathlon' is a long-distance triathlon competition that has been held annually in Norway since 2003. The inaugural event featured only 21 participants, but has since evolved into one of the most challenging triathlon competitions worldwide, exceeding even the demands of the traditional IRONMAN®-distance events [1]. 'Norseman Xtreme Triathlon' is unusually cold, has a variable environment and a high vertical load (distinct from most IRONMAN® races). These conditions involve unique physiological risks and evidence-based insights to athletes and their support could help optimize preparations. In order to preserve the extreme nature of the event, the number of participants is strictly limited to 250 athletes each year. Since 2010, starting slots have been allocated by lottery and are no longer on the basis of registration speed [2, 3].

The 'Norseman Xtreme Triathlon' starts from a ferry with a 3.8 km swim through the Hardangerfjord to Eidfjord, in a fjord, which means a narrow inlet of the sea between mountains, followed by a 180 km cycling course from Eidfjord via Hardangervidda, Geilo to Austbygde on Lake Tinnsjå. Finally, the marathon ran over 42.2 km to the summit of Mt. Gaustatoppen at an altitude of 1883 m. This IRONMAN®-distance triathlon covers an impressive 5200 m in altitude. Overall, the distances are the same as the IRONMAN® triathlon, but the increased demand is due to the nature of the event with swimming in cold

Extended author information available on the last page of the article

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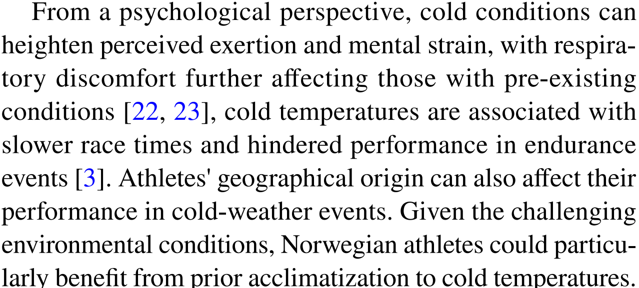
water, gains in altitude, and the need for a support crew during cycling and running [1].

In the 'Norseman Xtreme Triathlon', athletes swim in water temperatures of ~ 13–16 °C [4], cycle in temperatures of ~ 5–20 °C and run in temperatures of ~ 12–28 °C in the valley and ~ 2–12 °C on Mt. Gaustatoppen [3]. Particular challenges are the swim in the Hardangerfjord, which rarely exceeds 15 °C, and the final ascent over the scree to Gaustatoppen [1]. The typical weather at 42 km Mount Gaustatoppen is strong winds, rain and 2 °C. Most importantly, swimming in water below 16 °C is considered a risk of hypothermia [5].

At the ‘Norseman Xtreme Triathlon’, registration with a support team is mandatory, as there are no refreshment stations provided by the organizers on the bike course and at the start of the marathon course. Athletes must organize this themselves [1]. Given these extreme environmental and logistical challenges, participating in the ‘Norseman Xtreme Triathlon’ requires meticulous preparation and poses unique physiological risks, including risks for hypothermia [6], swimming-induced pulmonary edema (SIPE) [7], exercise-induced bronchoconstriction (EIB) [8] and exercise-induced arterial hypoxemia (EIAH) [9].

The cold environment appears to have a significant impact on the physiological and psychological challenges faced by endurance athletes. It impairs thermoregulation, increases the risk of hypothermia, frostbite and reduced muscle efficiency due to vasoconstriction and decreased peripheral blood flow [10]. The increased venoconstriction reduces blood flow to exercising muscles [11], increasing their reliance on anaerobic energy [12]. There is a greater accumulation of metabolites, such as H^+, that can impact the ability to contract muscles [13].

Cold also elevates metabolic demands, contributing to fatigue and diminished neuromuscular performance, while prolonging recovery and potentially compromising immune function during intense events such as the IRONMAN® Triathlon [14, 15]. However, training in cold weather may induce adaptations like improved muscle metabolism and fat oxidation, which has a positive effect on endurance, but also carries the risk of chronic fatigue if poorly managed [10]. Competing in cold environments forces athletes to consider adequate equipment [16] and nutrition [17]. A cold environment also has a considerable effect on the cardiovascular system [18]. Cold environment leads to an increase in body heat loss [19] and cold exposure is characterized by a sympathetic nervous system excitation leading to cutaneous vasoconstriction, elevated muscle sympathetic nerve activity and then to increases in arterial blood pressure [20]. Furthermore, swimming in cold water increases the risk to develop swimming-induced pulmonary edema as it has been reported for both open-water swimmers [7] and triathletes [21].



From a psychological perspective, cold conditions can heighten perceived exertion and mental strain, with respiratory discomfort further affecting those with pre-existing conditions [22, 23], cold temperatures are associated with slower race times and hindered performance in endurance events [3]. Athletes' geographical origin can also affect their performance in cold-weather events. Given the challenging environmental conditions, Norwegian athletes could particularly benefit from prior acclimatization to cold temperatures.

While literature from traditional IRONMAN® events provides useful general endurance context, the Norseman Xtreme Triathlon presents a fundamentally different physiological challenge due to cold-water swimming, substantial altitude gain, and prolonged exposure to environmental stress. These factors alter thermoregulation, pulmonary function, cardiovascular strain, and metabolic demands in ways that are not directly comparable to warm-weather long-course triathlons. Therefore, IRONMAN® comparisons in this review are used strictly for contextual contrast, with primary emphasis placed on ‘Norseman Xtreme Triathlon’-specific evidence.

Considering the above information, this narrative review aims to provide athletes and coaches with evidence-based insights to optimize preparation and performance for the ‘Norseman Xtreme Triathlon’. These findings could help future athletes and their coaches to better prepare for this unique challenge, especially regarding preparation about safety considering the cold environment.

Methods

This narrative review was conducted according to structured guidelines to ensure quality and transparency regarding the Scale for the Assessment of Narrative Review Articles (SANRA) [24]. Studies eligible for inclusion were those investigating athletes participating in or preparing for the ‘Norseman Xtreme Triathlon’.

Literature search strategy

The selected articles were related to the ‘Norseman Extreme Triathlon’ and were published up to the end of November 2025, with no language restrictions. The search for sources of high-quality scientific information was conducted using two of the most widely used information databases in the health and sports sciences—PubMed and Scopus [25]. Free-text terms were employed in the search [26]. The search strategy employed the terms ("Norseman" OR "Norseman Xtreme Triathlon" OR "Extreme Triathlon") in the PubMed and Scopus databases. A total of 17 articles were retrieved from PubMed and 13 from Scopus. After removing duplicates and screening titles and abstracts, studies that were not

directly related to the 'Norseman Xtreme Triathlon' were excluded. Additional studies were identified through manual screening of reference lists and citation tracking. Furthermore, Google Scholar ($n = 164$) was searched to identify any potentially missing references.

Eligibility criteria

Studies were included if they met the following criteria:

1. Investigated participants of the 'Norseman Xtreme Triathlon'.
2. Reported data on participation, performance, physiology, health outcomes, injuries, thermoregulation, nutrition, or economic aspects.
3. Were original peer-reviewed articles, case reports, conference proceedings with full data, or academic theses with empirical data.

Exclusion criteria were:

1. Studies not directly involving participants in 'Norseman Xtreme Triathlon'.
2. Narrative articles without original data.
3. Editorials, opinion pieces, and media reports.
4. Preprints where the study was not published.

Study selection

All identified records were screened independently by two authors based on title and abstract. Full-text screening was then performed to confirm eligibility. Disagreements were resolved by consensus. A total of 16 studies met the inclusion criteria and were included in the final synthesis (Fig. 1).

Data extraction and synthesis

For each included study, the following data were extracted (Table 1):

- Author and year
- Study design
- Sample size and participant characteristics
- Main outcome domain (*e.g.,* performance, cardiovascular, pulmonary, metabolic, thermoregulation)
- Key findings

Due to heterogeneity in study design and outcome measures, a qualitative narrative synthesis was performed rather than a meta-analysis.

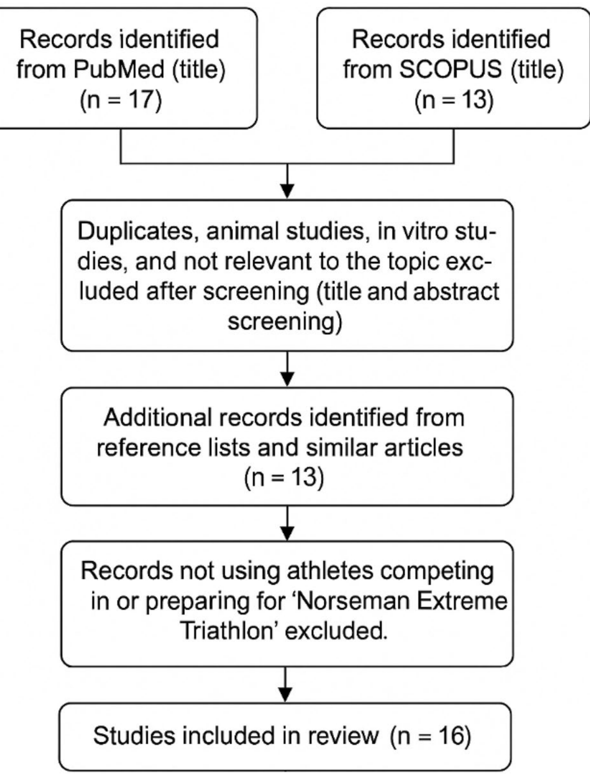


Fig. 1 Flowchart of the study selection

Results

Of the 16 included studies, 4 reported cardiovascular outcomes, 2 investigated exercise-induced bronchoconstriction (EIB), exercise-induced arterial hypoxemia (EIAH) and/or swimming-induced pulmonary edema (SIPE), 2 focused primarily on participation and performance trends, 2 examined cold-related responses, 1 assessed serum concentrations of metabolites, and 1 investigated overuse injuries. Several studies contributed data to more than one domain.

Participation and performance trends

Two studies investigated participation and performance trends among triathletes who participated in the 'Norseman Xtreme Triathlon' between 2006 and 2014 (Table 2) [2] and between 2003 and 2025 [3]. Over the years, the number of female and male finishers increased and the men-to-women participation ratio decreased from 16.2 in 2004 to 7.4 in 2015 [3]. Also, the overall race time decreased over the years, with the split times of all split disciplines decreasing [2]. Overall race time decreased every year, above all in the year 2012 [2]. However, another study found that women improved in swimming and both women and men improved in cycling and overall race time. In contrast, no significant improvement was found in running times for either sex [2].

Table 1 Overview of included studies investigating the 'Norseman Xtreme Triathlon'

Author	Study Design	Sample Size	Population	Main Domain	Key Outcomes
Rüst et al. [2]	Longitudinal observational	1000+	Male and female finishers	Participation trends	Increasing participation and narrowing sex difference over time
Melau et al. [27]	Case series	3	Norseman swimmers	Pulmonary	Late-onset swimming-induced pulmonary edema (SIPE) cases
Nyborg C et al. [28]	Field study	9	Norseman finishers	Metabolic	Marked post-race increases in inflammatory and metabolic biomarkers
Knechtle et al. [3]	Observational	1,050	Finishers	Sex differences	Persistent male performance dominance but trend toward convergence
Bonnevie-Svendsen et al. [29]	Field study	25	Finishers	Endothelial	Alterations in arginine, ADMA, SDMA and nitric oxide metabolites
Rüst et al. [2]	Observational	1200	Finishers	Nationality	Predominance of Norwegian athletes among finishers and podium placement
Høiseth et al. [4]	Field study	51	Finishers	Thermoregulation	Core temperature reductions during cold-water swim despite wetsuit use
Stensrud et al. [8]	Cross-sectional	63	Finishers	Pulmonary	46% with exercise-induced bronchoconstriction; 65% with arterial hypoxemia
Alexandrian [30]	Master's thesis	257	Norseman participants & crew	Economic impact	Estimated local economic impact ≈ 7 million NOK
Aktitiz [31]	Case study	1	Norseman finisher	Nutrition	In-race energy intake and metabolic response profiling
Andersen et al. [32]	Observational	174	Finishers	Injury epidemiology	Predominantly overuse injuries; low acute injury incidence

The most predictive split discipline was cycling [3]. Women were slower than men, but women narrowed the gap between the sexes year after year and especially in 2007 [3]. Another study found, however, that men were faster than women in cycling, but not in swimming, running and overall race time [2]. Participation and performance trends were also analysed by nationality. Most athletes who participated in the 'Norseman Xtreme Triathlon' were from Norway, and most podiums were achieved by athletes from Norway [2]. In addition, an annual analysis indicated that the three fastest Norwegian women improved in cycling, running, overall race time and transition times [2].

Metabolic aspects

One study assessed serum concentrations of metabolites for endothelial nitric oxide synthesis in triathletes one week following the 'Norseman Xtreme Triathlon' and found altered levels of metabolites for endothelial nitric oxide production that mostly normalized within one week following the race [29]. The clinical relevance of these findings needs to be elucidated in the athletic population. Another study investigated changes in common biomarkers after participation in the 'Norseman Xtreme Triathlon' and found significant changes in biomarkers used in a post-race clinical setting. Increased levels of clinical significance were seen at the finish line of the 'Norseman Xtreme Triathlon' in white blood cell count (WBC), creatinine kinase (CK) and N-terminal pro-brain natriuretic peptide (NT-proBNP). The following day, there were clinically significant changes in C-reactive protein (CRP) and Aspartate-Aminotransferase (AST) levels [33] (Table 3).

Table 2 Participation and performance trends in 'Norseman Xtreme Triathlon'

Study results	Reference
During 2003 to 2015, a total of 175 women (10.6%) and 1,852 men (89.4%) finished the race. The number of female and male finishers increased and the men-to-women ratio decreased. Men were faster than women in cycling (25.41 ± 2.84 km/h versus 24.25 ± 2.17 km/h), but not in swimming (3.06 ± 0.62 km/h vs. 2.94 ± 0.57 km/h), running (7.43 ± 1.13 km/h vs. 7.31 ± 0.93 km/h) and overall race time (874.57 ± 100.62 min vs. 899.95 ± 90.90 min). Over time, women improved in swimming and both women and men improved in cycling and in overall race time. In running, neither women nor men improved	[3]
Between 2006 and 2014 a total of 1594 athletes (139 women and 1455 men) from 34 different countries finished the race. Most of the athletes originated from Norway, Germany, Great Britain, Sweden, USA and France. In the mixed model analysis considering all finishers (n = 1594), with calendar year, sex and country as independent and overall race time as the dependent variable, calendar year, sex, country and the interaction sex × calendar year were significant. In the model where overall race time was separated in the three disciplines, interactions such as country × discipline, year × discipline, sex × discipline, calendar year × sex, calendar year × sex × discipline were significant. Overall race time decreased every year, above all in the year 2012. Women were slower than men, but women reduced this gap year after year and above all in the year 2007. Athletes from Norway and Germany were faster than those from Great Britain and other countries. Split times of the discipline decreased throughout the years. The discipline having more impact on the overall race time was cycling. Most of the podiums were achieved by Norwegian women and men. For women, the fastest split and transition times were achieved by Norwegian women except for the run where German women were faster. Norwegian men were the fastest in split and transition times, French athletes were the fastest in swimming. Across years, the annual three fastest Norwegian women improved in cycling, running, overall race time and transition times, but not Norwegian and German men. British men improved running split times and transition times	[2]

Cardiovascular system

A further topic in the research about 'Norseman Xtreme Triathlon' was the cardiovascular system (Table 4) [28, 29, 34, 35]. One study investigated the relationship between exercise-induced gut leakage and cardiac biomarker release and found that cardiac and gut leakage biomarkers increased after the 'Norseman Xtreme Triathlon'. However, the changes in these biomarkers were not intercorrelated and the clinical relevance of these findings has to be elucidated in the athletic population [34]. In another study, the circulatory levels of L-arginine, the L-arginine/asymmetric dimethylarginine (ADMA) ratio and symmetric dimethylarginine (SDMA) were examined before, after the race and on the day after the 'Norseman Xtreme Triathlon'. The results showed decreased levels of L-arginine and the L-arginine/ADMA ratio and increased levels of SDMA after the race. Since increased ADMA and SDMA levels and decreased L-arginine/ADMA ratio, as observed the day after the race, are known risk markers for atherosclerosis, these findings need to be further investigated [29]. In addition, another study assessed endothelial function by flow-mediated dilatation (FMD), levels of the NO-precursor L-arginine and markers of endothelial inflammation before, at the finish line and one week after the 'Norseman Xtreme Triathlon'. The markers for endothelial inflammation E-Selectin, VCAM-1 and ICAM-1 all showed a pattern of increased values after the race compared to before the race, with normalization within one week after the race [28].

Nutrition

Nutrition represents a critical factor in the preparation and execution of an extreme endurance event such as the 'Norseman Xtreme Triathlon'. In a case study of a 39-year-old male recreational triathlete competing in 'Norseman Xtreme Triathlon', nutritional intake during the race was analyzed [31]. The study highlighted that maintaining adequate energy and fluid intake throughout the event is challenging, but essential for sustaining performance and preventing gastrointestinal

Table 3 Metabolic aspects in 'Norseman Xtreme Triathlon'

Study results	Reference
Blood samples were collected before, after, and the day following the race in 98 subjects. Clinically significant increased levels were seen at the finish line of the Norseman in WBC (12.7 [11.1–15.9] 10^9/L, $p < 0.001$), CK (2450 [1620–3950] U/L, $p < 0.001$) and NT-proBNP (576 [331–856] ng/L, $p < 0.001$). CRP had an initial small increase at the finish line after the Norseman (8 [4–19] mg/L, $p < 0.001$) with a clinically significant increase the following day (39 [27–56] mg/L, $p < 0.001$ compared to baseline, < 0.001 compared to finish line). AST had increased at the finish line (99 [74–136] U/L, $p < 0.001$) but it increased to even higher values the day after the race (142 [99–191] U/L, $p < 0.001$ compared to baseline, $p < 0.05$ compared to finish line). CK had significantly increased at the finish line compared to baseline, and continued to increase. It displayed the highest values the day after the races (2910 [1650–4730] U/L, $p < 0.001$ compared to baseline)	[33]

WBC white blood cells, *CK* creatinine kinase, *NT-proBNP* N-terminal pro-B-type natriuretic peptide, *AST* Aspartate Aminotransferase, *ALT* Alanine Aminotransferase

Table 4 Effects on the cardiovascular system in 'Norseman Xtreme Triathlon'

Study results	Reference
Blood samples were taken before and after the race for biomarkers, cTnT and NT-proBNP in 44 participants (age 43 ± 9 yr, 9 [21%] women). Gut leakage marker LPS was measured by the kinetic, chromogenic limulus amebocyte lysate assay method, whereas LPS-binding protein (LBP), soluble cluster of differentiation 14 (sCD14), and intestinal injury marker I-FABP were measured by enzyme-linked immunosorbent assay. TnT and NT-proBNP increased significantly to 38 ng/l (27, 56) and 495 ng/l (310, 828) after the race. LBP and sCD14 increased significantly, as did I-FABP, whereas LPS remained unchanged. No significant correlations between changes in gut leakage markers and changes in cardiac biomarkers were observed	[34]
High-performance liquid chromatography was used to measure circulating concentrations of as L-arginine, ADMA and SDMA. Venous blood samples were collected before, after, day one, and one week following the race. Serum concentrations and L-arginine/ADMA ratio were determined for each time-point and compared to baseline. L-arginine/ADMA ratio was reduced on day one (147 ± 32 vs 163 ± 40). ADMA was reduced immediately after and increased at day one and remained elevated at one week (0.29 ± 0.05 µM, 0.44 ± 0.08 µM, and 0.42 ± 0.07 µM, respectively, vs 0.40 ± 0.05 µM). SDMA was increased at all time-points compared to baseline (0.48 ± 0.10 µM, 0.53 ± 0.11 µM, and 0.42 ± 0.08 µMvs 0.38 ± 0.05 µM). L-arginine was only decreased immediately after (46.0 ± 9.3 µM vs. 64.6 ± 16.1 µM)	[29]
To study the NO synthesis after prolonged exercise, circulatory L-arginine, the L-arginine/(ADMA ratio, and SDMA before, after, and on the day after the race were assessed. There were significantly reduced levels of L-arginine and the L-arginine/ADMA ratio and increased levels of SDMA after the race. L-arginine rose toward baseline levels the day after the race, ADMA increased beyond baseline levels, and SDMA remained above baseline the day after the race	[35]
Endothelial function by FMD, levels of the NO-precursor L-arginine, and markers of endothelial inflammation were assessed before, at the finish line, and one week after the race in 9 men. FMD was significantly reduced to 3.1 (2.1–5.0) % dilatation compared to 8.7 (8.2–9.3)% dilatation before the race and was normalized one week after the race. L-arginine showed significantly reduced levels at the finish but was normalized one week after the race. Markers of endothelial inflammation E-Selectin, VCAM-1, and ICAM-1 all showed a pattern with increased values at the finish line compared to before the race, with normalization one week after the race	[28]

cTnT cardiac troponin T, *TnT* troponin T, *NT-proBNP* N-terminal pro-B-type natriuretic peptide, *I-FABP* intestinal fatty acid binding protein, *ADMA* asymmetric dimethyl arginine, *SDMA* symmetric dimethyl arginine, *NO* nitric oxide, *FMD* flow-mediated dilatation, *VCAM-1* Vascular cell adhesion molecule 1, *ICAM-1* Intercellular Adhesion Molecule-1

distress, dehydration and hyponatremia – conditions commonly observed in ultra-endurance competitions. Another study investigated whether pre-race supplementation with phosphatidylcholine from krill oil could counteract the expected drop in choline and some of its metabolites during the 'Norseman Xtreme Triathlon'. It was shown that serum choline concentrations significantly decreased from pre- to post-race, with the decrease being more pronounced in the 'Norseman Xtreme Triathlon' compared to shorter distances. It was hypothesized that krill oil supplementation could potentially prevent critical depletion of circulating choline during prolonged endurance efforts, thereby supporting muscle function and neuromuscular transmission [36]. These findings are consistent with patterns observed in other ultra-endurance events, emphasizing the repetitive stress and cumulative trauma placed on the musculoskeletal system over prolonged periods of time.

Musculoskeletal system and overuse injuries

One study investigated overuse problems and acute injuries among participants of the 2011 'Norseman Xtreme Triathlon'. Most injuries in IRONMAN® triathletes are a result of overuse and occur far more frequently than acute injuries and illnesses. The most common injury sites in the study were the knee, the lower legs, the lower back and the shoulders [32] (Table 5).

Table 5 Musculoskeletal system and overuse injuries in 'Norseman Xtreme Triathlon'

Study results	Reference
A 26-week prospective cohort study was conducted, including 174 participants of the 2011 edition. Data on overuse injuries located in the shoulder, lower back, thigh, knee and lower leg were collected every second week using the Oslo Sports Trauma Research Center Overuse Injury Questionnaire. Illnesses, acute injuries and overuse problems affecting other anatomical areas were recorded using standard injury surveillance methods. The average prevalence of overuse problems was 56% (95% CI 51 to 61) (490 cases). The average prevalence of substantial overuse problems was 20% (95% CI 18 to 21) (165 cases). The most prevalent sites of overuse problems were the knee (25%), lower leg (23%) and lower back (23%). The acute injury incidence was 0.97 injuries per 1000 h of training (36 cases) and 1.02 injuries per 1,000 h of competition (5 cases). A majority of moderate and severe acute injuries were located at the knee, shoulder/clavicle and sternum/ribs. The predominant types of acute injuries were contusions, fractures and sprains. The incidence of illness was 5.3/1000 athlete-days (156 cases)	[32]

Pulmonary system

Extreme endurance events such as 'Norseman Xtreme Triathlon' also place considerable stress on the pulmonary system. Two studies have investigated the effect of race on lung function in participants in 'Norseman Xtreme Triathlon' (Table 6). In one study, lung function and oxygen saturation (SpO_2) were measured before the race, 8–10 min after the race and the day after the 'Norseman Xtreme Triathlon'. Nearly half of the participants presented with exercise-induced bronchoconstriction (EIB) and about two-thirds showed signs of exercise-induced arterial hypoxemia (EIAH) after the race [8]. A case study reported three cases of suspected late-presenting swimming-induced pulmonary edema (SIPE) during the 'Norseman Xtreme Triathlon' [27]. SIPE is an increasingly recognized risk among open-water swimmers, particularly in cold environments, and highlights the need for heightened awareness and screening for pulmonary complications in extreme endurance settings.

Table 6 Lung problems and SIPE in 'Norseman Xtreme Triathlon'

Study results	Reference
Exercise-induced bronchoconstriction (EIB) defined as ≥ 10% reduction in forced expiratory volume in one second (FEV_1) and exercise-induced arterial hypoxemia (EIAH) defined as ≥ 4% reduction in oxygen saturation (SpO_2) from before to after participation in the race were measured in 63 triathletes (50 men and 13 women) aged 40.3 ± 9.0 years. Fifty-seven (46 men and 11 women) measured lung function and 54 (44 men and 10 women) measured SpO_2 before the race, 8–10 min after the race (post-test 1) and the day after the race (post-test 2). Twenty-six participants (46%) presented with EIB at post-test 1 and 16 (28%) at post-test 2. Lung function variables were significantly reduced from baseline to post-test 1 and 2. Thirty-five participants (65%) showed evidence of mild to moderate EIAH. No significant correlations were observed except a weak correlation between maximal reduction in FEV_1 and respiratory symptoms	[8]
A case series on three cases of suspected late-presenting SIPE during the race. A 30-year-old male professional triathlete, a 40-year-old female age group triathlete and a 34-year-old male age group triathlete presented with shortness of breath, chest tightness and coughing up pink sputum during the last part of the bike phase. All three athletes reported an improvement in breathing during the first major uphill of the bike phase and increasing symptoms during the downhill. The professional triathlete had a thoracic computed tomography, and the scan showed bilateral ground glass opacity in the peripheral lungs. The male age group athlete had a normal chest x-ray. Both athletes were admitted for further observation and discharged from hospital the following day, with complete regression of symptoms. The female athlete recovered quickly following pre-hospital oxygen treatment	[27]

EIB Exercise-induced bronchoconstriction, *EIAH* Exercise-induced arterial hypoxemia, *SIPE* Swimming-Induced Pulmonary Edema

Cold water and body core temperature

Cold water immersion during the swim segment poses a substantial thermoregulatory challenge. Swimming in cold water affects human health and performance depending on the experience of the participant; it can be beneficial for experienced athletes but detrimental to participants unfamiliar with this exercise practice [5]. Two studies have investigated the effect of cold water on body core temperature in participants in 'Norseman Xtreme Triathlon' (Table 7) [4, 37]. One study investigated the effect of cold water on body core temperature in 51 participants. During the swim in water temperatures of ~15–16 °C, subjects with a low body mass index and long swimming times may be at risk of hypothermia, even if they are wearing a wetsuit [4]. In another study, 20 subjects swam in a wetsuit in 10 °C water. Although no participant experienced a core temperature drop greater than 2 °C within the first 30 min, the findings underline the importance of limiting the duration of swimming in colder water to mitigate the risk of significant hypothermia [36].

Economic impact of the race

Included from the reference lists of the studies in PubMed and Scopus, a master thesis investigated the direct economic impact of the 'Norseman Xtreme Triathlon' on the municipality of Eidfjord [30]. The visitors of the event

Table 7 Cold water and body core temperature

Study results	Reference
The core temperature of 51 participants who ingested temperature sensor capsules before the swim leg of the race were measured. The water temperature was 14.4–16.4 °C, and the subjects wore wetsuits. One subject with a low BMI and a long swim time experienced hypothermia (< 35 °C). Among the remaining subjects, no association between core temperature and swim time, body mass index, or sex was found	[4]
To investigate the physiological response when swimming in a wetsuit in 10 °C water. Twenty triathletes, 37.6 ± 9 years (12 males and 8 females) performed open water swimming in 10 °C seawater; while Tre and Tskin were recorded. Tre was maintained for the first 10–15 min of the swim; and no participants dropped more than 2 °C in Tre during the first 30 min of swimming in 10 °C water. According to extrapolations of the results, during a swim time above 135 min; 47% (8/17) of the participants in the present study would fall more than 2 °C in Tre during the swim	[37]

Tre rectal temperature, *Tskin* skin temperature

invested in accommodation, food and drinks, entertainment, tourist activities, local traveling and parking. The total, locally relevant, direct expenditure was calculated to be ~7,000,000 Norwegian Krone (NOK), equivalent to around ~667,747 United States Dollars (USD), and this expenditure was considered as an injection of “new wealth” to the local economy [30].

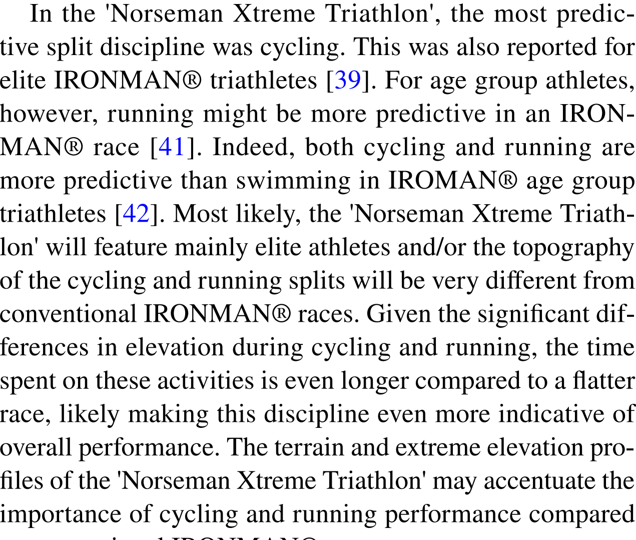
Discussion

This narrative review aimed to synthesize the current scientific evidence on participation, performance trends, physiological responses and environmental challenges associated with the ‘Norseman Xtreme Triathlon’. The main findings were that participation has increased over the years, with a gradual reduction in the male-to-female ratio. Performance improvements were mainly noted in cycling and overall race time, while the physiological effect of the race included transient changes in metabolic, cardiovascular and pulmonary markers. Despite the growing interest in the event, the scientific literature remains limited, especially regarding nutrition and long-term adaptations to the cold environment.

Participation and performance trends

The 'Norseman Xtreme Triathlon' has seen an increase in the number of women and men participating. Similar upward trends in participation have been documented in traditional IRONMAN® events such as the IRONMAN® World Championship in Hawaii [37, 38]. Unfortunately, in the 'Norseman Xtreme Triathlon', the increase in age group athletes was not investigated. In IRONMAN® races, however, the number of female and male age group (master) athletes increased over the years [37, 38]. For example, an analysis of over 800,000 race records from IRONMAN® 70.3 events found that older athletes—particularly those aged 50 and above—are increasingly closing the performance gap between the sexes [37].

In the 'Norseman Xtreme Triathlon', depending on the study, split and overall race times decreased over the years, while in another study, running times did not improve. These disparate findings might be due to the sample size and/or the period studied. In IRONMAN® races such as IRONMAN® Hawaii, both women and men significantly improved their performances [39]. When changes in split times in IRONMAN® races between 1989 and 2014 were analyzed from the top 50 overall male and female finishers, cycling and running splits and total time decreased. In contrast, the swimming time remained stable for both men and women [40]. Most likely, the different changes over time in the split disciplines in both the 'Norseman Xtreme Triathlon' and the IRONMAN® are due to the different samples.



In the 'Norseman Xtreme Triathlon', the most predictive split discipline was cycling. This was also reported for elite IRONMAN® triathletes [39]. For age group athletes, however, running might be more predictive in an IRONMAN® race [41]. Indeed, both cycling and running are more predictive than swimming in IROMAN® age group triathletes [42]. Most likely, the 'Norseman Xtreme Triathlon' will feature mainly elite athletes and/or the topography of the cycling and running splits will be very different from conventional IRONMAN® races. Given the significant differences in elevation during cycling and running, the time spent on these activities is even longer compared to a flatter race, likely making this discipline even more indicative of overall performance. The terrain and extreme elevation profiles of the 'Norseman Xtreme Triathlon' may accentuate the importance of cycling and running performance compared to conventional IRONMAN® events.

In terms of sex differences, the results of the 'Norseman Xtreme Triathlon' are also varied. Depending on the study, men were faster than women in overall and split times, whereas another study reported that men were only faster than women in cycling. These disparate findings might be due to the sample size and/or the period studied. In IRONMAN® races, however, men were always faster than women in all groups for all split disciplines and overall race times [43]. The inconsistent findings in the 'Norseman Xtreme Triathlon' are most likely due to smaller sample sizes and the extreme environmental challenges unique to the event.

Local Norwegian athletes dominate the ‘Norseman Xtreme Triathlon’ in both participation and performance. This mirrors the findings from IRONMAN® events where European athletes, particularly from Switzerland, Germany and Austria, have been shown to achieve the fastest overall race times [44, 45], although US triathletes are generally the most numerous [45, 46]. The dominance of Norwegian athletes in the ‘Norseman Xtreme Triathlon’ is most likely because Norwegian triathletes are used to the cold weather [47]. The geographical proximity could also have an influence on the larger number of Norwegian participants in the competition [2].

Effects on the different systems

Only a few studies have investigated the potential effects of the ‘Norseman Xtreme Triathlon’ on organ systems such as the metabolism, the cardiovascular system and the pulmonary system. Given the long duration and high metabolic demands, a major concern of the researchers was post-race recovery [48, 49]. In terms of metabolism, the largest clinical importance was the clinically significant elevation of WBC, CRP, AST, CK, and NT-proBNP after the ‘Norseman Xtreme Triathlon’. These findings indicate a systemic inflammatory response, muscle damage and cardiac strain

after the race. Increases in CK, AST and ALT are common findings after an IRONMAN® triathlon, reflecting skeletal muscle breakdown and hepatocellular stress [50]. Mujika et al. reported substantial elevations in these markers immediately after an IRONMAN® triathlon, with CK levels often exceeding several thousand IU/L, and a gradual normalization over several days, highlighting the significant physiological stress imposed by extreme endurance racing [50]. In the abovementioned research, it was concluded that full recovery occurred one week after an IRONMAN® triathlon lasting 8–9 h. However, it should be noted that direct physiological comparisons with warm-weather IRONMAN® events [51] should be interpreted with caution due to the fundamentally different environmental stressors of the 'Norseman Xtreme Triathlon' [27].

Regarding the cardiovascular system, the studies primarily used biomarkers, but we found no study that performed echocardiographic examinations. In contrast, other studies that examined IROMAN® triathletes used cardiovascular magnetic resonance (CMR) [52] or echocardiography [53, 54]. Ricci et al. [52] detected transient myocardial edema in master triathletes after an IRONMAN® triathlon using CMR, indicating subclinical myocardial stress. Similarly, echocardiographic studies [53, 54] demonstrated acute changes in cardiac function, particularly right ventricular size and function, predictive of race performance. Future research on the 'Norseman Xtreme Triathlon' could greatly benefit from integrating echocardiography or CMR to provide more detailed insights into cardiac adaptations and possible transient dysfunction following such an extreme event. It should be highlighted that strenuous sport activities may cause reversible changes in the cardiovascular system with complete recovery within a few days [55].

SIPE can occur in the 'Norseman Xtreme Triathlon', most likely due to the very cold water temperatures and the tight wetsuits used [56, 57]. Barouch [56] emphasized that SIPE is an underrecognized cause of triathlon-related medical emergencies, and a systematic review by Hohmann et al. [57] reported its association with cold-water swimming. Although three cases of SIPE were reported at the 'Norseman Xtreme Triathlon', this represents a relatively low prevalence. In triathlon races, the prevalence of SIPE is estimated to be at ~1.4% [21, 57, 58]. The lower prevalence in the 'Norseman Xtreme Triathlon' could be due to the participants being better acclimatized to the cold conditions.

Effects on the locomotor system

An IRONMAN® triathlon induces a bone-formative-favoring turnover during the post-race period for male age group triathletes [59]. Wu and Huang [59] demonstrated that participating in an IRONMAN® triathlon race induced a bone turnover shift favoring bone formation in amateur male triathletes during the post-race recovery period. This bone-formative response is likely a compensatory mechanism for the mechanical loading and systemic stress experienced during the race. To date, no equivalent study has investigated bone turnover following the 'Norseman Xtreme Triathlon', which represents a valuable avenue for future research.

Effects on body core temperature

Due to the cold water during the 'Norseman Xtreme Triathlon', two studies investigated the effect of cold water on body core temperature. Mild to moderate hypothermia was observed in some athletes, reflecting the unique thermal stress of the 'Norseman Xtreme Triathlon' compared to traditional triathlons. In contrast, other triathlons, such as IROMAN® Hawaii [60] or IRONMAN® Western Australia [61] pose the opposite challenge. Due to the high temperatures in Hawaii, body core temperature increased during the marathon run in IRONMAN® Hawaii [60], putting athletes at risk of heat-related illnesses. Similarly, Laursen et al. [61] found a significant increase in core temperature and signs of dehydration during IRONMAN® Western Australia. These contrasting thermal challenges highlight the need for race-specific preparation and medical monitoring strategies, depending on the environmental conditions of the event.

Nutrition at the 'Norseman Xtreme Triathlon'

From a systems perspective, nutritional intake during the 'Norseman Xtreme Triathlon' represents a cross-cutting modifier of thermoregulation, metabolic strain, hydration status, and renal load [62], rather than an isolated performance variable. We found only one case report on nutrition at the 'Norseman Xtreme Triathlon'. In IROMAN® triathlon races, the nutrition aspect was better investigated [63, 64] by analysing the intake of carbohydrates [63] and the prevalence of gastrointestinal symptoms [63]. Pfeiffer et al. [63] reported that a higher carbohydrate intake was associated with improved performance, but also with a higher incidence of gastrointestinal complaints. There are even specific nutritional recommendations for competing in an IROMAN® triathlon, including strategies to optimize carbohydrate loading, hydration and gastrointestinal tolerance [64]. However, due to the unique environmental conditions and extreme demands of the 'Norseman Xtreme Triathlon', particularly the cold temperatures, the nutritional requirements might differ significantly from those established for traditional IRONMAN® events. For an IRONMAN® triathlon, athletes need to consume enough carbohydrate and fluids during the race [64]. In 'Norseman Xtreme Triathlon', the needs for energy and fluid intakes are similar than for an IRONMAN® triathlon, however, athletes need to organize their food and fluid intake with their personal support crew

[31]. Future studies should focus on better characterizing the specific nutritional demands of athletes competing in the ‘Norseman Xtreme Triathlon’, including carbohydrate intake, hydration strategies and the potential impact of cold exposure on energy expenditure and gastrointestinal tolerance.

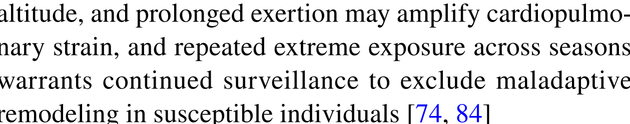
Integrative physiological framework of the stress in ‘Norseman Xtreme Triathlon’

The physiological responses observed during the ‘Norseman Xtreme Triathlon’ can be interpreted within an integrated environmental–systems framework. The primary external stressors—cold exposure during prolonged swimming and early cycling, hypoxia associated with altitude gain, and sustained eccentric muscular load during mountainous running—act synergistically to challenge pulmonary gas exchange, cardiovascular regulation, metabolic homeostasis, and renal function [65]. These effects manifest as acute race-day responses (*e.g.,* bronchoconstriction, arterial hypoxemia, cardiac biomarker release, and muscle damage), followed by short-term recovery adaptations during the post-race period [66]. Framing the results within this stressor–system–time course model provides a unifying structure for understanding performance limitation, physiological risk, and recovery in this extreme endurance environment [67].

Clinical interpretation of biomarker responses

The post-race elevations observed in CK [68], cTnT [69, 70], and NT-proBNP [71, 72] must be interpreted within the context of ultra-endurance physiology [73–75]. CK concentrations in athletes competing in ‘Norseman Xtreme Triathlon’ frequently exceed 2000–3000 U/l at the finish line, values that are markedly above conventional clinical reference ranges [76] but remain consistent with levels commonly reported after prolonged endurance exercise [77] and are typically attributable to reversible skeletal muscle membrane disruption rather than rhabdomyolysis in adequately hydrated athletes [68, 78]. NT-proBNP is a marker of myocardial stress. The main stimulus for both proBNP synthesis and secretion from cardiac myocytes is myocyte stretch [79]. Similarly, transient post-exercise increases in cTNT and NT-proBNP are well-documented after ultra-endurance events and are considered to reflect acute myocardial strain and ventricular wall stress rather than irreversible myocardial injury, particularly when values normalize within 24–72 h [80–82].

The available data from ‘Norseman Xtreme Triathlon’ indicate that these cardiac biomarkers return to baseline during short-term recovery [83], supporting a predominantly benign and adaptive cardiac response in well-screened athletes [73]. Nonetheless, the combination of cold exposure,



altitude, and prolonged exertion may amplify cardiopulmonary strain, and repeated extreme exposure across seasons warrants continued surveillance to exclude maladaptive remodeling in susceptible individuals [74, 84]

Risk stratification and medical implications in the Norseman Xtreme Triathlon

The ‘Norseman Xtreme Triathlon’ exposes athletes to a unique convergence of pulmonary, cardiovascular, and renal stressors [85] that warrant structured risk stratification rather than isolated interpretation. In this context, SIPE has been documented in participants in ‘Norseman Xtreme Triathlon’, with case series indicating that cold-water immersion, tight wetsuit compression, and elevated pulmonary vascular pressures may act synergistically to precipitate acute respiratory compromise. Although the absolute prevalence remains uncertain, the condition is now recognized as an underdiagnosed but potentially life-threatening complication of cold open-water endurance swimming also in triathletes [21]. Pre-race screening for prior SIPE episodes, arterial hypertension, and reduced pulmonary compliance may, therefore, be warranted in high-risk athletes [7].

Similarly, exercise-induced arterial hypoxemia (EIAH) has been reported in approximately two-thirds of the tested participants in ‘Norseman Xtreme Triathlon’, indicating that an impaired pulmonary gas exchange is not a rare phenomenon in this race environment. Cold-induced bronchoconstriction, diffusion limitation at high cardiac outputs, and altitude-related reductions in arterial oxygen tension likely contribute to this response [86]. From a practical standpoint, athletes with a history of asthma, bronchial hyperresponsiveness, or previous hypoxemic episodes may benefit from targeted pulmonary screening and individualized inhalation strategies under medical supervision [87].

With respect to renal function, acute kidney stress following ultra-endurance exercise is typically transient and driven by dehydration, rhabdomyolysis risk, and renal hypoperfusion [88]. While overt acute kidney injury has not been systematically quantified in participants in ‘Norseman Xtreme Triathlon’, the combination of prolonged exertion, cold exposure, and high eccentric load supports the need for routine post-race renal monitoring in symptomatic athletes [89]. Early identification of creatinine elevation, reduced urine output, or electrolyte disturbances is essential to prevent progression to clinically significant injury [90].

Collectively, these observations indicate that specific medical risk management should extend beyond general endurance race protocols for ‘Norseman Xtreme Triathlon’. Practical measures may include targeted pre-race pulmonary screening [91], structured medical observation during the cold-water swim exit [5], conservative hydration strategies tailored for cold environments [92], and post-race

surveillance for cardiopulmonary and renal complications in high-risk finishers [93].

Practical applications for athletes and coaches preparing for 'Norseman Xtreme Triathlon'

To counteract the cold during the three disciplines, athletes could either increase their body's subcutaneous fat reserves to protect themselves against the cold [89]. Or they have to wear special clothing like a very thick wetsuit and heavy clothes when cycling and running [16]. Since the athletes may need their own crew during cycling and running, they can rely on support vehicles and strategically placed refreshment stations in this area [94].

A further aspect is cold-related training and/or acclimation to the cold [95]. Cold acclimation improves training capacity in cold climates and optimizes warm-up strategies [20]. Acclimation protocols can decrease cold injury risk and stabilize core temperature [20]. Cold training can enhance athletes' performance and health by boosting recovery, improving endurance, and strengthening mental resilience [89].

Race courses in IRONMAN® triathlons are predominantly flat, where athletes achieve fast cycling and running split times [45]. In 'Norseman Xtreme Triathlon', however, the full race covers 5200 m change in altitude, where the marathon to the summit of Mt. Gaustatoppen at an altitude of 1883 m needs also a climb during running. Cycling and running speed during an IRONMAN® triathlon seems to considerably vary velocity varied with changes in elevation [96]. Furthermore, race course characteristic such as gain in elevation seem to be a major predictor in ultra-marathon running [97, 98], where change in elevation is the most important predictor for 100 km ultra-marathon performance [97]. Therefore, any athlete intending to compete in 'Norseman Xtreme Triathlon' needs to consider training for changes in altitude and selecting the appropriate equipment to master climbs during cycling and running [99, 100].

Limitations

A limitation is the low number of research studies, their design, the lack of comparison with other events. The scientific evidence base concerning the 'Norseman Xtreme Triathlon' is characterized by substantial methodological heterogeneity. The included studies range from large retrospective performance analyses to small observational field studies, single-case reports, and postgraduate theses. While participation trends, sex differences, and pacing behavior are supported by relatively robust data, many physiological and medical findings, particularly those related to pulmonary complications and renal stress, are derived from limited sample sizes or isolated observations. This heterogeneity restricts causal inference and limits definitive conclusions regarding athlete safety and long-term health consequences. Most available data describe acute, short-term physiological responses, whereas high-quality longitudinal studies on chronic adaptation and long-term clinical risk are lacking. In addition, the strict qualification criteria and high fitness level of participants in 'Norseman Xtreme Triathlon' constrain the generalizability of these findings to broader endurance-sport populations. Consequently, safety-related conclusions should be interpreted as hypothesis-generating rather than definitive, and future research should prioritize prospective longitudinal monitoring and standardized medical screening protocols. However, the present review will serve as a reference for anyone preparing for, studying, or medically supporting this uniquely demanding race.

Specific recommendations for athletes, coaches and support crews before and during 'Norseman Xtreme Triathlon'

Athletes, coaches, and support crews should focus on acclimatization, equipment checks, nutrition, and mental readiness when preparing for cold-water swimming, hilly cycling, and mountain climbing. Each discipline requires tailored strategies to minimize risk and maximize performance. By combining smart acclimatization, technical preparation, and strong support systems, athletes can tackle cold swims, hilly rides, and mountain climbs with resilience and efficiency.

General pre-race preparation

Before competing in such an extreme race, you need to consider training or competing under similar conditions. Alternatively, you may stay in the support crew of another athlete in order to gain experience for this kind of race. The support crew must strictly follow the instructions of the race organization. You need to prepare your car following the prescription of the organization. Consider different kinds of food (commercial products such as energy bars or gels, specially prepared nutrition for the specific needs of the athlete, hot water ready in a thermos for warm soup, warm tea). Bring enough warm clothing in case you need to change your clothes. Bring enough spare parts for the bike.

Swimming in cold water

Acclimatization: Water for the swim is between 13 and 17 °C. Gradually expose yourself to cold water in training to reduce the cold shock response (*e.g.,* gasping, hyperventilation). Consider competing pre-race in a cold-water swim to check and test your equipment.

Equipment: Consider the thickest wetsuit and/or wear additional clothes under the wetsuit. Gloves and swim socks

are permitted. Ensure that your wetsuit fit properly. Neoprene caps, earplugs, and gloves can help retain warmth.

Before the swim start: Splash cold water on your face, head, and inside your wetsuit before entering the cold water to reduce the cold shock.

During the swim split: Practice steady breathing to counteract involuntary gasping.

Cycling on a hilly course

Course-specific training: Practice climbs and descents during training. Focus on pacing uphill and technical handling downhill.

Bicycle: Test pre-race that you have the optimum equipment including the equipment for the.

mandatory backpack that needs to be packed before arriving at Eidfjord. Ensure brakes, gears, and tires are in top condition. Carry appropriate spares.

Nutrition: Consider carry energy bars and or carbohydrate gels in case your support crew will miss you. Fuel before climbs; small carbohydrate-rich snacks can prevent energy dips.

Support Crew: Be sure that your car is fully equipped with all spare material, nutrition, clothes. Be ready to provide logistical support (nutrition hand-offs, mechanical backup). Support crew members must follow the rules set by the race organization. An athlete will be penalized or disqualified if the support team causes dangerous situations.

Gear check: Ensure brakes, gears, and tires are in top condition. Carry appropriate spares. The bike must have working lights mounted front and rear. The reflective vest provided by the race organization must be used during the first 36 km of the bike leg.

Emergency/survival bag: Check that you have the bag as described by the organizer.

Running on a mountain

Pre-race preparation: Consider running a mountain marathon with similar environmental conditions, such as strong winds, rain, and 2 °C to test your equipment (*e.g.,* running shoes, clothes, backpack system). Try out different backpack systems on the climb. Try out different foods and drinks that hold up well in the cold.

Equipment: Consider the recommendations of the race organization regarding equipment for a mountain marathon in the cold. Proper footwear, layered clothing, hydration packs, and safety equipment are needed. Athletes and support must carry their mandatory backpacks from km 37.

Food and drinks: Consider taking all necessary nutrition with you in the backpack system in case your support crew will miss you.

Emergency/survival bag: Check that you have the bag as described by the organizer.

Recommendations for future research

Collectively, the available data support a distinction between predominantly acute, reversible race-day physiological perturbations and short-term recovery adaptations, whereas true long-term maladaptive remodeling remains insufficiently characterized in athletes competing in Norseman Xtreme Triathlon'. Given the limited amount of data on nutritional strategies during the 'Norseman Xtreme Triathlon', further studies are needed that focus on the optimization of carbohydrate and fluid intake in cold environments, the prevalence and prevention of gastrointestinal issues during the race, and the individual nutritional needs of athletes in extreme conditions. This information could contribute to better prepare athletes and their coaches for the unique challenges of the 'Norseman Xtreme Triathlon'. No study has investigated the variability in the participant profiles regarding age, sex, training and previous experience. Furthermore, aspects such as post-race recovery trajectories, hormonal profiles, or psychological responses have not been investigated. Future studies also need to investigate cost–benefit analyses, including tourism data and municipal budgets. Alterations in arginine and derivates from arginine, including ADMA, SDMA and NO are of importance to endothelial function and vasodilatation [101]. Arginine has been studied regarding athletic performance and found to show potential to improve aerobic and anaerobic performance [102]. A possible benefit of arginine supplements might be investigated in future studies.

Conclusions

Due to the cold environment, athletes participating in the 'Norseman Xtreme Triathlon' appear to be at increased risk of developing hypothermia and swimming-induced pulmonary edema (SIPE) during the swim segment, as well as exercise-induced bronchoconstriction (EIB) and exercise-induced arterial hypoxemia (EIAH) following the race. These findings provide valuable information for athletes and coaches aiming to optimize race preparation. Particular attention should be paid to cold water and cold weather strategies for both cycling and running segments. In addition, the specific nutritional demands, the aspects of pre-race preparation (*e.g.* training, experience), post-race recovery trajectories, hormonal profiles, or psychological responses of the 'Norseman Xtreme Triathlon' remain underexplored and represent an important area for future research.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

References

1. Introducing the Norseman Xtreme Triathlon, www.lifeinnorway.net/norseman-triathlon/. Accessed 8 Dec 2025.
2. Rüst CA, Bragazzi NL, Signori A, Stiefel M, Rosemann T, Knechtle B (2015) Nation related participation and performance trends in "Norseman Xtreme Triathlon" from 2006 to 2014. Springerplus 4(1):469. https://doi.org/10.1186/s40064-015-1255-5
3. Knechtle B, Nikolaidis PT, Stiefel M, Rosemann T, Rüst CA (2016) Performance and sex differences in "Isklar Norseman Xtreme Triathlon." Chin J Physiol 59(5):276–283. https://doi.org/10.4077/CJP.2016.BAE420
4. Høiseth LØ, Melau J, Bonnevie-Svendsen M, Nyborg C, Eijsvogels TMH, Hisdal J (2021) Core temperature during cold-water triathlon swimming. Sports Basel 9(6):87. https://doi.org/10.3390/sports9060087
5. Knechtle B, Waśkiewicz Z, Sousa CV, Hill L, Nikolaidis PT (2020) Cold water swimming-benefits and risks: a narrative review. Int J Environ Res Public Health 17(23):8984. https://doi.org/10.3390/ijerph17238984
6. Feletti F, Saini G, Naldi S, Casadio C, Mellini L, Feliciani G, Zamprogno E (2022) Injuries in medium to long-distance triathlon: a retrospective analysis of medical conditions treated in three editions of the Ironman competition. J Sports Sci Med 21(1):58–67. https://doi.org/10.52082/jssm.2022.58
7. Spencer S, Dickinson J, Forbes L (2018) Occurrence, risk factors, prognosis and prevention of swimming-induced pulmonary oedema: a systematic review. Sports Med Open 4(1):43. https://doi.org/10.1186/s40798-018-0158-8
8. Stensrud T, Rossvoll Ø, Mathiassen M, Melau J, Illidi C, Østgaard HN, Hisdal J, Stang J (2020) Lung function and oxygen saturation after participation in Norseman Xtreme Triathlon. Scand J Med Sci Sports 30(6):1008–1016. https://doi.org/10.1111/sms.13651
9. Galy O, Hue O, Chamari K, Boussana A, Chaouachi A, Préfaut C (2008) Influence of performance level on exercise-induced arterial hypoxemia during prolonged and successive exercise in triathletes. Int J Sports Physiol Perform 3(4):482–500. https://doi.org/10.1123/ijspp.3.4.482
10. Bubnis MA, Hulsopple C (2022) Human performance and injury prevention in cold weather environments. Curr Sports Med Rep 21(4):112–116. https://doi.org/10.1249/JSR.0000000000000946
11. Alba BK, Castellani JW, Charkoudian N (2019) Cold-induced cutaneous vasoconstriction in humans: function, dysfunction and the distinctly counterproductive. Exp Physiol 104(8):1202–1214. https://doi.org/10.1113/EP087718
12. Joyner MJ, Casey DP (2015) Regulation of increased blood flow (hyperemia) to muscles during exercise: a hierarchy of competing physiological needs. Physiol Rev 95(2):549–601. https://doi.org/10.1152/physrev.00035.2013
13. de Freitas MC, Gerosa-Neto J, Zanchi NE, Lira FS, Rossi FE (2017) Role of metabolic stress for enhancing muscle adaptations: practical applications. World J Methodol 7(2):46–54. https://doi.org/10.5662/wjm.v7.i2.46
14. Mueller SM, Knechtle P, Knechtle B, Toigo M (2015) An ironman triathlon reduces neuromuscular performance due to impaired force transmission and reduced leg stiffness. Eur J Appl Physiol 115(4):795–802. https://doi.org/10.1007/s00421-014-3051-2
15. Angelova M, Holloway PM, Shelyag S, Rajasegarar S, Rauch HGL (2021) Effect of stress on cardiorespiratory synchronization of Ironman athletes. Front Physiol 12:612245. https://doi.org/10.3389/fphys.2021.612245
16. Fudge J (2016) Preventing and managing hypothermia and frostbite injury. Sports Health 8(2):133–139. https://doi.org/10.1177/1941738116630542
17 Wilson PB, Pyne DB, Rotunno A (2025) UCI Sports nutrition project: the role of nutrition in the prevention and management of illnesses and injuries in elite cycling. Int J Sport Nutr Exerc Metab. 20:1–17. https://doi.org/10.1123/ijsnem.2025-0144. (**Epub ahead of print. PMID: 41265430**)
18. Manou-Stathopoulou V, Goodwin CD, Patterson T, Redwood SR, Marber MS, Williams RP (2015) The effects of cold and exercise on the cardiovascular system. Heart 101(10):808–820. https://doi.org/10.1136/heartjnl-2014-306276
19. Seltenrich N (2015) Between extremes: health effects of heat and cold. Environ Health Perspect 123(11):A275–A280. https://doi.org/10.1289/ehp.123-A275
20 Wakabayashi H (2025) Physiological Responses and Performance in Cold Environments. In: Tochihara Y (ed) The Thermal Environment. Springer, Singapore
21. Knechtle B, Nikolaidis PT, Chlíbková D, Bernardes Leite L, Forte P, Santos Andrade M, Weiss K, Rosemann T, Duric S (2025) Swimming-induced pulmonary oedema in triathletes: a narrative review of epidemiology, risk factors and prevention. Sports Med Health Sci. https://doi.org/10.1016/j.smhs.2025.08.004
22. Falla M, Micarelli A, Hüfner K, Strapazzon G (2021) The effect of cold exposure on cognitive performance in healthy adults: a systematic review. Int J Environ Res Public Health 18(18):9725. https://doi.org/10.3390/ijerph18189725
23. Hyrkäs-Palmu H, Jaakkola MS, Mäkikyrö EMS, Jaakkola JJK (2022) Subtypes of asthma and cold weather-related respiratory symptoms. Int J Environ Res Public Health 19(14):8790. https://doi.org/10.3390/ijerph19148790
24. Baethge C, Goldbeck-Wood S, Mertens S (2019) SANRA-a scale for the quality assessment of narrative review articles. Res Integr Peer Rev 4:5. https://doi.org/10.1186/s41073-019-0064-8
25. Falagas ME, Pitsouni EI, Malietzis GA, Pappas G (2008) Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. FASEB J 22(2):338–342. https://doi.org/10.1096/fj.07-9492LSF
26. DeMars MM, Perruso C (2022) MeSH and text-word search strategies: precision, recall, and their implications for library instruction. J Med Libr Assoc 110(1):23–33. https://doi.org/10.5195/jmla.2022.1283
27. Melau J, Bonnevie-Svendsen M, Mathiassen M, Mykland Hilde J, Oma L, Hisdal J (2019) Late-Presenting Swimming-Induced

Pulmonary Edema: A Case Report Series from the Norseman Xtreme Triathlon. Sports 7(6):137. https://doi.org/10.3390/sports7060137
28. Nyborg C, Melsom HS, Bonnevie-Svendsen M, Melau J, Seljeflot I, Hisdal J (2021) Transient Reduction of FMD-Response and L-Arginine Accompanied by Increased Levels of E-Selectin, VCAM, and ICAM after Prolonged Strenuous Exercise. Sports 9(6):86. https://doi.org/10.3390/sports9060086
29. Bonnevie-Svendsen M, Nyborg C, Bratseth V, Melau J, Hisdal J (2024) Transient changes in L-arginine, asymmetric and symmetric dimethyl arginine in triathletes following Norseman Xtreme Triathlon. Front Physiol 15:1451038. https://doi.org/10.3389/fphys.2024.1451038
30. Alexandrian, Josephine. The economic impact of Norseman Xtreme Triathlon 2013, Master thesis, University of Agder, 2014 School of Business and Law, https://uia.brage.unit.no/uia-xmlui/bitstream/handle/11250/219126/BE-501%202014%20sping%20Master%60s%20thesis%20Josephine%20Alexandrian.pdf?sequence=1&isAllowed=y
31. Aktitiz S (2024) Case study: nutrition planning intake during Norseman extreme triathlon in a recreational athlete nutrition intake for extreme triathlon. Curr Sports Med Rep 23(10):327–331. https://doi.org/10.1249/JSR.0000000000001197
32. Andersen CA, Clarsen B, Johansen TV, Engebretsen L (2013) High prevalence of overuse injury among iron-distance triathletes. Br J Sports Med 47(13):857–861. https://doi.org/10.1136/bjsports-2013-092397
33. Nyborg C, Melau J, Bonnevie-Svendsen M, Mathiasen M, Melsom HS, Storsve AB, Hisdal J (2020) Biochemical markers after the Norseman extreme triathlon. PLoS ONE 15(9):e0239158. https://doi.org/10.1371/journal.pone.0239158
34. Aune SK, Bonnevie-Svendsen M, Nyborg C, Trøseid M, Seljeflot I, Hisdal J, Helseth R (2022) Gut leakage and cardiac biomarkers after prolonged strenuous exercise. Med Sci Sports Exerc 54(9):1476–1482. https://doi.org/10.1249/MSS.0000000000002948
35. Nyborg C, Bonnevie-Svendsen M, Melsom HS, Melau J, Seljeflot I, Hisdal J (2021) Reduced L-Arginine and L-Arginine-ADMA-Ratio, and Increased SDMA after Norseman Xtreme Triathlon. Sports 9(9):120. https://doi.org/10.3390/sports9090120
36. Storsve AB, Johnsen L, Nyborg C, Melau J, Hisdal J, Burri L (2020) Effects of krill oil and race distance on serum choline and choline metabolites in triathletes: a field study. Front Nutr 7:133. https://doi.org/10.3389/fnut.2020.00133
37. Melau J, Mathiassen M, Stensrud T, Tipton M, Hisdal J (2019) Core temperature in triathletes during swimming with wetsuit in 10 °C cold water. Sports (Basel) 7(6):130. https://doi.org/10.3390/sports7060130
38. Knechtle B, Valero D, Villiger E, Thuany M, Andrade MS, Nikolaidis PT, Cuk I, Weiss K (2023) Comparing the performance gap between males and females in the older age groups in IRONMAN® 70.3: an internet-based cross-sectional study of more than 800,000 race records. Sports Med Open 9(1):88. https://doi.org/10.1186/s40798-023-00636-x
39. Barbosa LP, Sousa CV, Sales MM, Olher RDR, Aguiar SS, Santos PA, Tiozzo E, Simões HG, Nikolaidis PT, Knechtle B (2019) Celebrating 40 years of Ironman: how the champions perform. Int J Environ Res Public Health 16(6):1019. https://doi.org/10.3390/ijerph16061019
40. Figueiredo P, Marques EA, Lepers R (2016) Changes in contributions of swimming, cycling, and running performances on overall triathlon performance over a 26-year period. J Strength Cond Res 30(9):2406–2415. https://doi.org/10.1519/JSC.0000000000001335
41. Sousa CV, Aguiar S, Olher RR, Cunha R, Nikolaidis PT, Villiger E, Rosemann T, Knechtle B (2021) What is the best discipline to predict overall triathlon performance? An analysis of sprint, Olympic, Ironman® 70.3, and Ironman® 140.6. Front Physiol 12:654552. https://doi.org/10.3389/fphys.2021.654552
42. Knechtle B, Valero D, Villiger E, Thuany M, Cuk I, Forte P, Andrade MS, Nikolaidis PT, Rosemann T, Weiss K (2025) Cycling and running are more predictive of overall race finish time than swimming in IRONMAN® age group triathletes. Sports Med Open 11(1):30. https://doi.org/10.1186/s40798-025-00835-8
43. Knechtle B, Valero D, Villiger E, Thuany M, Andrade MS, Cuk I, Nikolaidis PT, Rosemann T, Weiss K (2024) Sex difference in IRONMAN age group triathletes. PLoS ONE 19(10):e0311202. https://doi.org/10.1371/journal.pone.0311202
44. Knechtle B, Villiger E, Weiss K, Valero D, Rosemann T, Nikolaidis PT, Vancini RL, Andrade MS, Thuany M (2025) The fastest nonprofessional age group IRONMAN triathletes in the world originate from Europe. Sci Rep 15(1):1028. https://doi.org/10.1038/s41598-024-84008-9.PMID:39762336;PMCID:PMC11704204
45. Knechtle B, Thuany M, Valero D, Villiger E, Nikolaidis PT, Cuk I, Rosemann T, Weiss K (2024) Europe has the fastest Ironman race courses and the fastest Ironman age group triathletes. Sci Rep 14(1):20903. https://doi.org/10.1038/s41598-024-71866-6
46. Dähler P, Rüst CA, Rosemann T, Lepers R, Knechtle B (2014) Nation related participation and performance trends in "Ironman Hawaii" from 1985 to 2012. BMC Sports Sci Med Rehabil 6(1):16. https://doi.org/10.1186/2052-1847-6-16
47. Reasons Why Norseman is King, www.triathlete.com/events/8-reasons-why-norseman-is-king/, Accessed 29 Nov 2025
48. Etxebarria N, Mujika I, Pyne DB (2019) Training and competition readiness in triathlon. Sports 7(5):101. https://doi.org/10.3390/sports7050101
49. Roete AJ, Elferink-Gemser MT, Otter RTA, Stoter IK, Lamberts RP (2021) A systematic review on markers of functional overreaching in endurance athletes. Int J Sports Physiol Perform 16(8):1065–1073. https://doi.org/10.1123/ijspp.2021-0024
50. Mujika I, da Pereira Silveira F, Nosaka K (2017) Blood markers of recovery from Ironman distance races in an elite triathlete. J Sports Med Phys Fitness 57(7–8):1057–1061. https://doi.org/10.23736/S0022-4707.16.06390-8
51. Knechtle B, Thuany M, Valero D, Villiger E, Nikolaidis PT, Andrade MS, Cuk I, Rosemann T, Weiss K (2025) The association of origin and environmental conditions with performance in professional IRONMAN triathletes. Sci Rep 15(1):2700. https://doi.org/10.1038/s41598-025-86033-8
52. Ricci F, Aquaro GD, De Innocentiis C, Rossi S, Mantini C, Longo F, Khanji MY, Gallina S, Pingitore A (2022) Exercise-induced myocardial edema in master triathletes: insights from cardiovascular magnetic resonance imaging. Front Cardiovasc Med 9:908619. https://doi.org/10.3389/fcvm.2022.908619
53. Bianchini E, Bruno RM, Di Lascio N, Vezzoli A, Mrakic-Sposta S, Corciu AI, Comassi M, Pratali L (2019) Acute cardiovascular adaptation to strenuous exercise: an integrative ultrasound study. J Ultrasound Med 38(2):463–470. https://doi.org/10.1002/jum.14719
54. Bernheim AM, Attenhofer Jost CH, Zuber M, Pfyffer M, Seifert B, De Pasquale G, Linka A, Faeh-Gunz A, Medeiros-Domingo A, Knechtle B (2013) Right ventricle best predicts the race performance in amateur ironman athletes. Med Sci Sports Exerc 45(8):1593–1599. https://doi.org/10.1249/MSS.0b013e31828ba558
55. Graziano F, Juhasz V, Brunetti G, Cipriani A, Szabo L, Merkely B, Corrado D, D'Ascenzi F, Vago H, Zorzi A (2022) May strenuous endurance sports activity damage the cardiovascular system of healthy athletes? A narrative review. J Cardiovasc Dev Dis 9(10):347. https://doi.org/10.3390/jcdd9100347

56. Barouch LA (2022) Swimming-induced pulmonary edema: an underrecognized cause of triathlon-associated medical emergencies. JACC Case Rep 4(17):1094–1097. https://doi.org/10.1016/j.jaccas.2022.05.019
57. Hohmann E, Glatt V, Tetsworth K (2018) Swimming induced pulmonary oedema in athletes - a systematic review and best evidence synthesis. BMC Sports Sci Med Rehabil 10(1):18. https://doi.org/10.1186/s13102-018-0107-3
58. Miller CC 3rd, Calder-Becker K, Modave F (2010) Swimming-induced pulmonary edema in triathletes. Am J Emerg Med 28(8):941–946. https://doi.org/10.1016/j.ajem.2009.08.004
59. Wu CC, Huang TH (2019) The effects of a 226-km ironman triathlon race on bone turnover in amateur male triathletes. J Sports Med Phys Fitness 59(10):1709–1715. https://doi.org/10.23736/S0022-4707.19.09564-1
60. Olcina G, Crespo C, Timón R, Mjaanes JM, Calleja-González J (2019) Core temperature response during the marathon portion of the Ironman World Championship (Kona-Hawaii). Front Physiol 10:1469. https://doi.org/10.3389/fphys.2019.01469
61. Laursen PB, Suriano R, Quod MJ, Lee H, Abbiss CR, Nosaka K, Martin DT, Bishop D (2006) Core temperature and hydration status during an Ironman triathlon. Br J Sports Med 40(4):320–325. https://doi.org/10.1136/bjsm.2005.022426
62. Périard JD, Eijsvogels TMH, Daanen HAM (2021) Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev 101(4):1873–1979. https://doi.org/10.1152/physrev.00038.2020
63. Pfeiffer B, Stellingwerff T, Hodgson AB, Randell R, Pöttgen K, Res P, Jeukendrup AE (2012) Nutritional intake and gastrointestinal problems during competitive endurance events. Med Sci Sports Exerc 44(2):344–351. https://doi.org/10.1249/MSS.0b013e31822dc809
64. Robins A (2007) Nutritional recommendations for competing in the Ironman triathlon. Curr Sports Med Rep 6(4):241–248 (**PMID: 17618000**)
65. Jdidi H, Dugué B, de Bisschop C, Dupuy O, Douzi W (2024) The effects of cold exposure (cold water immersion, whole- and partial- body cryostimulation) on cardiovascular and cardiac autonomic control responses in healthy individuals: a systematic review, meta-analysis and meta-regression. J Therm Biol 121:103857. https://doi.org/10.1016/j.jtherbio.2024.103857
66. Iellamo F (2024) Acute responses and chronic adaptations to exercise in humans: a look from the autonomic nervous system window. J Sports Med Phys Fitness 64(2):137–150. https://doi.org/10.23736/S0022-4707.23.15353-9
67. Berger NJA, Best R, Best AW, Lane AM, Millet GY, Barwood M, Marcora S, Wilson P, Bearden S (2024) Limits of ultra: towards an interdisciplinary understanding of ultra-endurance running performance. Sports Med 54(1):73–93. https://doi.org/10.1007/s40279-023-01936-8
68. Clarkson PM, Kearns AK, Rouzier P, Rubin R, Thompson PD (2006) Serum creatine kinase levels and renal function measures in exertional muscle damage. Med Sci Sports Exerc 38(4):623–627. https://doi.org/10.1249/01.mss.0000210192.49210.fc
69. Scharhag J, George K, Shave R, Urhausen A, Kindermann W (2008) Exercise-associated increases in cardiac biomarkers. Med Sci Sports Exerc 40(8):1408–1415. https://doi.org/10.1249/MSS.0b013e318172cf22
70. Scharhag J, Shave R, George K, Whyte G, Kindermann W (2008) Exercise-induced increases in cardiac troponins in endurance athletes: a matter of exercise duration and intensity? Clin Res Cardiol 97(1):62–63. https://doi.org/10.1007/s00392-008-0601-9
71. Scharhag J, Herrmann M, Urhausen A, Haschke M, Herrmann W, Kindermann W (2005) Independent elevations of N-terminal pro-brain natriuretic peptide and cardiac troponins in endurance athletes after prolonged strenuous exercise. Am Heart J 150(6):1128–1134. https://doi.org/10.1016/j.ahj.2005.01.051
72. Scharhag J, Meyer T, Auracher M, Müller M, Herrmann M, Gabriel H, Herrmann W, Kindermann W (2008) Exercise-induced increases in NT-proBNP are not related to the exercise-induced immune response. Br J Sports Med 42(5):383–385. https://doi.org/10.1136/bjsm.2007.039529
73. Knechtle B, Nikolaidis PT (2018) Physiology and pathophysiology in ultra-marathon running. Front Physiol 9:634. https://doi.org/10.3389/fphys.2018.00634
74. O'Keefe JH, Patil HR, Lavie CJ, Magalski A, Vogel RA, McCullough PA (2012) Potential adverse cardiovascular effects from excessive endurance exercise. Mayo Clin Proc 87(6):587–595. https://doi.org/10.1016/j.mayocp.2012.04.005
75. Dockerill C, Lapidaire W, Lewandowski AJ, Leeson P (2020) Cardiac remodelling and exercise: what happens with ultra-endurance exercise? Eur J Prev Cardiol 27(14):1464–1466. https://doi.org/10.1177/2047487320904511
76. Doles N, Ye Mon M, Shaikh A, Mitchell S, Patel D, Seehusen D, Singh G (2025) Interpretating normal values and reference ranges for laboratory tests. J Am Board Fam Med 38(1):174–179. https://doi.org/10.3122/jabfm.2024.240224R1
77. Giovanelli N, Lazzer S, Cauci S (2020) Muscle damage and inflammatory status biomarkers after a 3-stage trail running race. J Sports Med Phys Fitness 60(11):1486–1492. https://doi.org/10.23736/S0022-4707.20.10997-6
78. Bäcker HC, Richards JT, Kienzle A, Cunningham J, Braun KF (2023) Exertional rhabdomyolysis in athletes: systematic review and current perspectives. Clin J Sport Med 33(2):187–194. https://doi.org/10.1097/JSM.0000000000001082
79. Hall C (2005) NT-ProBNP: the mechanism behind the marker. J Card Fail 11(5 Suppl):S81–S83. https://doi.org/10.1016/j.cardfail.2005.04.019
80. Baggish AL, Wood MJ (2011) Athlete's heart and cardiovascular care of the athlete: scientific and clinical update. Circulation 123(23):2723–2735. https://doi.org/10.1161/CIRCULATIONAHA.110.981571
81. La Gerche A, Burns AT, Mooney DJ, Inder WJ, Taylor AJ, Bogaert J, Macisaac AI, Heidbüchel H, Prior DL (2012) Exercise-induced right ventricular dysfunction and structural remodelling in endurance athletes. Eur Heart J 33(8):998–1006. https://doi.org/10.1093/eurheartj/ehr397
82. Baker P, Leckie T, Harrington D, Richardson A (2019) Exercise-induced cardiac troponin elevation: an update on the evidence, mechanism and implications. Int J Cardiol Heart Vasc 22:181–186. https://doi.org/10.1016/j.ijcha.2019.03.001
83. Legaz-Arrese A, Carranza-García LE, Navarro-Orocio R, Valadez-Lira A, Mayolas-Pi C, Munguía-Izquierdo D, Reverter-Masía J, George K (2017) Cardiac biomarker release after endurance exercise in male and female adults and adolescents. J Pediatr 191:96–102. https://doi.org/10.1016/j.jpeds.2017.08.061
84. Frandsen J, Aaroe M, Sehestedt T, Sahl RE, Hansen MT, Lie-Olesen MM, Nielsen AB, Rømer T, Ingersen A, Larsen S, Dela F, Sacchetti M, Cataldo A, Traina M, Helge JW, Rasmusen HK (2025) Cardiac effects of prolonged endurance exercise in young and older athletes. Scand J Med Sci Sports 35(7):e70104. https://doi.org/10.1111/sms.70104
85. Husain-Syed F, McCullough PA, Birk HW, Renker M, Brocca A, Seeger W, Ronco C (2015) Cardio-pulmonary-renal interactions: a multidisciplinary approach. J Am Coll Cardiol 65(22):2433–2448. https://doi.org/10.1016/j.jacc.2015.04.024
86. Krebs KE, Fletcher J, Tiso MR (2023) Evaluation and Treatment of Cold- and Altitude-Related Injuries and Illnesses. In: Miller TL (ed) Endurance Sports Medicine. Springer, Cham
87. Ora J, De Marco P, Gabriele M, Cazzola M, Rogliani P (2024) Exercise-induced asthma: managing respiratory issues in

athletes. J Funct Morphol Kinesiol 9(1):15. https://doi.org/10.3390/jfmk9010015

88. Tidmas V, Brazier J, Bottoms L, Muniz D, Desai T, Hawkins J, Sridharan S, Farrington K (2022) Ultra-endurance participation and acute kidney injury: a narrative review. Int J Environ Res Public Health 19(24):16887. https://doi.org/10.3390/ijerph192416887
89. Gatterer H, Dünnwald T, Turner R, Csapo R, Schobersberger W, Burtscher M, Faulhaber M, Kennedy MD (2021) Practicing sport in cold environments: practical recommendations to improve sport performance and reduce negative health outcomes. Int J Environ Res Public Health 18(18):9700. https://doi.org/10.3390/ijerph18189700
90. Yang H, Chen Y, He J, Li Y, Feng Y (2025) Advances in the diagnosis of early biomarkers for acute kidney injury: a literature review. BMC Nephrol 26(1):115. https://doi.org/10.1186/s12882-025-04040-3
91. Sewry N, Schwellnus M, Borjesson M, Swanevelder S, Jordaan E (2020) Pre-race screening and stratification predicts adverse events-a 4-year study in 29585 ultra-marathon entrants, SAFER X. Scand J Med Sci Sports 30(7):1205–1211. https://doi.org/10.1111/sms.13659
92. Murray R (1995) Fluid needs in hot and cold environments. Int J Sport Nutr Exerc Metab 5:S62-73. https://doi.org/10.1123/ijsn.5.s1.s62
93. Kim JH, Baggish AL, Levine BD, Ackerman MJ, Day SM, Dineen EH, Guseh IJS, La Gerche A, Lampert R, Martinez MW, Papadakis M, Phelan DM, Shafer KM, Allen LA, Börjesson M, Braverman AC, Brothers JA, Castelletti S, Chung EH, Churchill TW, Claessen G, D'Ascenzi F, Darden D, Dean PN, Dickert NW, Drezner JA, Economy KE, Eijsvogels TMH, Emery MS, Etheridge SP, Gati S, Gray B, Halle M, Harmon KG, Hsu JJ, Kovacs RJ, Krishnan S, Link MS, Maron M, Molossi S, Pelliccia A, Salerno JC, Shah AB, Sharma S, Singh TK, Stewart KM, Thompson PD, Wasfy MM, Wilhelm M (2025) Clinical considerations for competitive sports participation for athletes with cardiovascular abnormalities: a scientific statement from the American Heart Association and American College of Cardiology. J Am Coll Cardiol 85(10):1059–1108. https://doi.org/10.1016/j.jacc.2024.12.025
94. Knechtle B, Knechtle P, Rüst CA, Rosemann T, Lepers R (2011) Finishers and nonfinishers in the 'Swiss Cycling Marathon ' to qualify for the 'Race Across America '. J Strength Cond Res 25(12):3257–3263. https://doi.org/10.1519/JSC.0b013e31821606b3
95. Wang Y, Liu W, Han D, Qiao Y, Sun W, Wang C, Qin X, Xu J (2025) Integrated effects of cold acclimation: physiological mechanisms, psychological adaptations, and potential applications. Front Physiol 16:1609348. https://doi.org/10.3389/fphys.2025.1609348
96. Pryor JL, Adams WM, Huggins RA, Belval LN, Pryor RR, Casa DJ (2018) Pacing strategy of a full Ironman overall female winner on a course with major elevation changes. J Strength Cond Res 32(11):3080–3087. https://doi.org/10.1519/JSC.0000000000002807
97. Knechtle B, Weiss K, Valero D, Scheer V, Villiger E, Nikolaidis PT, Andrade M, Cuk I, Gajda R, Rosemann T, Thuany M (2025) Change in elevation predicts 100 km ultra marathon performance. Sci Rep 15(1):25176. https://doi.org/10.1038/s41598-025-09502-0
98. Knechtle B, Villiger E, Weiss K, Valero D, Gajda R, Scheer V, de Lira CAB, Braschler L, Nikolaidis PT, Vancini RL, Cuk I, Rosemann T, Thuany M (2024) Analysis of the 72-hour ultramarathon using a predictive XG Boost model. Sport Sci Health. https://doi.org/10.1007/s11332-024-01243-3
99. Scheer V, Vieluf S, Bitter N, Christ L, Heitkamp HC (2020) The optimal weight carriage system for runners: comparison between handheld water bottles, waist belts, and backpacks. Front Physiol 11:571221. https://doi.org/10.3389/fphys.2020.571221
100. Scheer V, Vieluf S, Schröder M, Lappe P, Heitkamp HC (2020) A comparison of economy between two different backpack designs for runners. Appl Ergon 84:103038. https://doi.org/10.1016/j.apergo.2019.103038
101. Cyr AR, Huckaby LV, Shiva SS, Zuckerbraun BS (2020) Nitric oxide and endothelial dysfunction. Crit Care Clin 36(2):307–321. https://doi.org/10.1016/j.ccc.2019.12.009
102. Viribay A, Burgos J, Fernández-Landa J, Seco-Calvo J, Mielgo-Ayuso J (2020) Effects of arginine supplementation on athletic performance based on energy metabolism: a systematic review and meta-analysis. Nutrients 12(5):1300. https://doi.org/10.3390/nu12051300

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