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REVIEW ARTICLE

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24-Hour Ultra-Marathon Running: A Narrative Review of Performance Factors and Physiological Impacts

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Abstract

The 24-hour ultra-marathon is a specific race format with a long tradition and high popularity. To date, no comprehensive review has systematically summarized the scientific literature on 24-hour ultra-marathon running. We performed a comprehensive search in the PubMed and Scopus databases, covering studies published until the end of 2025. The participation of runners and finishers in 24-hours has increased in the past decades. Most participants in 24-hours are age group or master runners older than 35 years. 24-hour ultra-runners typically cover distances exceeding 100 km per event, with an average distance ranging from ~150–160 km, while the top performers can achieve over 200 km. Men achieve greater distances than women. The best performance is achieved at 40–50 years. The most important predictive variables in 24-hours are training, nutrition, previous experience, and pacing; anthropometric characteristics seemed of no predictive value. During 24-hours, athletes ingest mainly carbohydrates and experience an energy deficit, but rarely exercise-associated hyponatremia. A 24-hour run leads to decrease in body mass, which can be due to dehydration, a loss of skeletal muscle mass, and/or a loss of fat mass. A 24-hour run has effects on the cardiovascular system (i.e., decrease in blood pressure, changes in cardiac biomarkers, and changes in electrocardiogram and echocardiographic findings), the kidneys (i.e. reversible impairment of kidney function), the digestive system (i.e., gastrointestinal discomfort, reversible increase in liver enzymes), the immune system (i.e., increase in immune markers) and the hematological system (i.e., decrease in red blood cells, increase in white blood cells). All negative effects are resolved within 2–3 days. In summary, 24-hour ultra-marathon runners are master athletes with extensive experience, optimal training preparation, and optimal nutrition to complete a 24-hour run successfully. The adverse effects on the heart, kidneys, immune system, and digestive tract generally resolve within a few days after the event. Future studies need to investigate nutrition after the race to enhance recovery and the impact of training and competing in this specific race format on the locomotor system (i.e. skeleton, muscles, tendons, joints).

Key Points

- The number of runners in 24-hour ultra-marathons has increased globally, with a significant increase among master athletes (35 + years).

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- Training, nutrition, previous experience, and pacing are essential for optimizing performance.
- Men continue to cover greater distances than women, but this gap has been decreasing over time.
- The race influences multiple body systems, but most changes resolve within a few days.
- Further studies should concentrate on post-race recovery and the long-term effects of ultra-marathon running on the musculoskeletal system.

Keywords 24-hour running, Training, Nutrition, Heart, Liver, Kidney, Hyponatremia

Background

The 24-hour ultra-marathon is a particular ultra-marathon race format with both a long tradition and a high popularity [1, 2]. Competitors must run as far as possible within 24 h, and the total kilometers completed at the end of the race indicates performance. These races are usually held on short loops, often on 400-meter tracks. These events offer runners diverse environments and challenges, all focused on the 24-hour ultra-marathon format.

Historically, the first 24-hour race took place in 1807 in Newmarket (UK), featuring two participants. In 2024, over 300 events were held worldwide, attracting thousands of finishers [1]. As the popularity of this race format continues to grow, so does scientific interest in the area. Therefore, we aim to summarize the current literature in a narrative review. The purpose of this review is to provide a comprehensive and integrative synthesis of the existing literature, particularly in emerging or interdisciplinary fields within ultra-marathons. This synthesis will cover various perspectives, contextualize findings, and identify research gaps.

Several reviews on ultra-marathon running have been published, including reviews focusing on the motivation of ultra-marathon runners [3], the limitations of ultra-endurance running performance [4], cytokines in ultra-marathon running [5], potential long-term health problems in ultra-marathon running [6], limiting factors in ultra-marathon running [7], nutritional considerations in ultra-marathon running [8], pulmonary and respiratory muscle function in ultra-marathon running [9], physiology and pathophysiology in ultra-marathon running [10], and running-related musculoskeletal injuries [11]. However, to date, no comprehensive review has systematically summarized the scientific literature on 24-hour ultra-marathon running. We aimed to focus on important topics such as participation and performance trends, training and pacing, nutrition, fluid metabolism, and energy balance are essential in maintaining endurance, with particular attention to fluid intake and hydration management, exercise-associated hyponatremia (EAH), and changes in body mass (i.e. fat mass, skeletal muscle mass), all of which can affect race completion and health outcomes.

Main Text

Aim

To date, there is no comprehensive review of the scientific output on 24-hour ultra-marathon running. A summary of this scientific knowledge could help athletes and coaches better prepare for the race. Therefore, we aimed to summarize the existing knowledge in a narrative review. We collected literature to provide a thorough overview of this topic.

Methods

The present study was designed as a narrative review. The relevant literature was searched using a predefined search algorithm [12]. The selected articles pertained to 24-hour ultra-marathon running and were published up until the end of December 2025, with no language restrictions. The search was conducted for sources of high-quality scientific information utilizing two of the most widely used information databases in health and sports sciences – PubMed and SCOPUS [13]. Free text words were employed in the search [14]. The following search terms were used: ((24-hour) OR (24 h) OR (24 h) OR (24 h) OR (24-h)) AND ((run) OR (running) OR (race)). We found 46 articles in the PubMed database (title) and 59 articles in SCOPUS (title). Duplicate records and studies unrelated to the scope of this review (e.g., multi-stage races, ultra-cycling, mountain biking, ultra-swimming) were excluded after the initial screening of titles and abstracts. A total of 62 references were then kept for the review. Further relevant studies were identified among the reference lists of the selected full-text papers and through searches of similar articles and citations (PubMed database). Studies that did not examine the performance-related factors of ultra-marathoners were excluded from the analysis.

Data Extraction

The data extraction was organized into topics to provide a structured analysis of the key factors influencing performance, participation trends, and physiological responses in 24-hour ultra-marathons. Understanding participation trends helps track the growth of the sport by identifying demographic shifts and emerging patterns over time. Relatedly, the analysis of performance in

24-hour ultra-marathons allows for benchmarking both elite and amateur runners, while examining sex differences in performance and age-related trends reveals how physiological factors influence endurance capabilities. Furthermore, investigating the changes in sex differences over time and determining the age of peak performance provide insights into whether endurance advantages shift across different groups of athletes. A deeper understanding of the variables that influence performance is gained by analyzing anthropometric characteristics, such as body composition and weight, in conjunction with training variables and previous experience. These factors help assess the impact of preparation and race history. Pacing strategies are another crucial element, determining how well runners manage their energy distribution over 24 h of running. The effects of ultra-endurance running on different body systems were also categorized for a comprehensive physiological assessment. Cardiovascular effects explore how the heart adapts to prolonged exertion, while renal function is examined to assess risks such as acute kidney injury (AKI). The impact on the gastrointestinal system highlights common issues like nausea and gut distress, whereas changes in the immune system and hematological system provide insight into post-race recovery and long-term health implications. Additionally, oxidative stress is analyzed to determine the extent of physiological strain, while the skeletal and locomotor systems are investigated to assess injury risks and musculoskeletal adaptations. Psychological and recovery-related aspects were also considered, as motivation and fatigue play crucial roles in performance and influence how athletes cope with extreme exertion. Similarly, stress and recovery were examined to understand hormonal responses, sleep deprivation, and overall recuperation. By structuring the data into these categories, the review ensures a comprehensive synthesis of research on 24-hour ultra-marathon running, providing valuable insights into the interplay of physiological, psychological, and performance-related factors in this extreme endurance event.

Results

Participation Trends in 24-Hour Ultra-Marathon Running

The study of participation trends offers valuable insights into various aspects, including the sex and age of participants, changes over the years, a comparison of this race format with other time-limited race formats, and variations in participation by age group. Over the years, runner participation in this race format has increased [15, 16]. In comparison to shorter race durations like 6-hour and 12-hour races, more men participated in the longer 24-hour race format [2]. Participation among women and men varied by age, showing relatively low involvement of women in the older age groups [17]. Typically, participants in 24-hour races are age group or masters' runners aged 35 years and older [15, 16, 18–20]. However, youth runners under the age of 19 years also participate in this race format. A study investigating youth runners who competed in 24-hour ultra-marathons between 1990 and 2018 found that there were 805 finishes from 582 unique finishers recorded [21].

Performance in a 24-Hour Ultra-Marathon

The performance in a 24-hour race is evaluated based on the distance covered within this time frame, which can typically be assessed during a field race; this performance was also recorded on a laboratory treadmill. Table 1 summarizes the 24-hour ultra-marathon performances reported in the studies [22–40], of which two [29, 40] were performed under laboratory conditions on a treadmill. Generally, 24-hour ultra-runners achieve more than100 km in such an event [22–39], with the average being ~ 150–160 km [22–39] and the best runners achieving over 200 km [25]. Research has shown that, under laboratory conditions during treadmill running, running speed remained constant for the first six hours before significantly decreasing over the remainder of the 24-hour period [40]. Interestingly, performance in 24-hour ultra-marathons decreased over decades [16]. The performance gap between sexes has decreased, yet men still manage to achieve longer distances in 24-hour ultra-marathon events.

Sex Differences in 24-Hour Ultra-Marathon Running

Table 2 summarizes the differences in performance between sexes as reported in the studies. Several studies examined the sex differences in this race format [16, 17, 19, 41]. Overall, men were faster than women [16], with the percentage of sex differences depending on the sample studied (i.e., all women and men, annual top 100, annual top 10, or annual top 1) [19]. In absolute terms, comparing running speed for top 10 ever, top 100 ever and all finishers between 1977 and 2012, men ran significantly faster by 12.9 ± 0.8%, 12.2 ± 0.4%, and 4.6 ± 0.5%, respectively [19]. Although the performance gap between male and female ultra-marathon runners has narrowed over time, men still manage to cover longer distances in 24-hour events [16, 17, 19, 41].

Age and Sex Differences in Performance

An important aspect of the sex difference in performance is age. As age increases, the sex gap widens in 24-hour running [17]. In absolute terms, the sex difference increased from 2.6% at the age of 36 years to 4.6% at the age of 56 years [17]. The age of peak performance has increased for men while remaining consistent for women,

Table 1 Performance in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Bossi et al. [22]	*N* = 501, Female = 103	Retrospective	24-h ultra-marathon	Distance achieved in 24 h.	Mean overall performance was 135.6 ± 33.0 km with a mean effective-running time of 22.4 ± 1.3 h.
Charlot et al. [23]	*N* = 12, Female = 6	Prospective	24-hour World Championship	Investigation of the fluctuations of food and fluid intake during the 24-h World Championship.	Total distance run was 193–272 km.
Shimizu et al. [24]	*N* = 16, Female = 0	Descriptive field study	Experimental 24-h run	Investigation of inflammatory responses during and after running and changes in stress responses as determined by serial changes in blood components.	Mean running distance in 24 h was 151.32 ± 32.1 km (range 83.6–210.0 km).
Takayama et al. [25]	*N* = 48, Female = 0	Prospective	24-h ultra-marathon	Influence of pacing on 24-h ultra-marathon performance in different performance groups.	Ten fastest runners (Group A) covered a mean distance of 236.38 ± 11.41 km whereas 40th -48th fastest runners (Group E) covered a mean of 164.14 ± 2.49 km.
Knechtle et al. [26]	*N* = 15, Female = 0	Descriptive field study	24-h ultra-marathon	Influence of anthropometry, training, and prior marathon performance on 24-h ultra-marathon performance.	The runners achieved an average performance of 180.7 ± 29.4 km.
Knechtle et al. [27]	*N* = 22, Female = 0	Cross-sectional	24-h ultra-marathon	Association between skin-fold thickness and training characteristics with 24-h ultra-marathon performance.	A mean distance of 154 ± 47 km was achieved during the race.
Knechtle et al. [28]	*N* = 63, Female = 0, Age 46.9 ± 10.3 yrs	Retrospective	24-h ultra-marathon	Relation between anthropometric and training characteristics with 24-h ultra-marathon performance.	A mean distance of 146.1 ± 43.1 km was achieved during the race.
Millet et al. [29]	*N* = 14 Female = 0 Age 41.1 ± 8.9 yrs	Prospective	24-h treadmill ultra-marathon	Physiological performance-related factors in 24-h ultra-marathon.	Mean distance covered was 149.2 ± 15.7 km.
Niemelä et al. [30]	*N* = 13, Female = 0, Age (yrs) 38 ± 8	Prospective	24-h ultra-marathon	LV function after a 24-h ultra-marathon in experienced male ultra-marathoners.	Mean distance covered was 173 ± 33 km.
Knechtle et al. [31]	*N* = 63, Female = 0, Age 46.9 ± 10.3 yrs	Retrospective	24-h ultra-marathon	Association between leg skinfold thickness and 24-h ultra-marathon race performance.	Mean distance of 146.1 ± 43.1 km was achieved during the race.
Ohta et al. [32]	*N* = 15, Female = 3	Field study	24-h ultra-marathon	Subjective symptoms were investigated using the Japanese version of the POMS instrument.	Participants ran a mean distance of 162.6 ± 18.3 km.
Passaglia et al. [33]	*N* = 20 Female = 0 Age 43.3 ± 9.9 yrs	Prospective	24-h ultra-marathon	Effects of a 24-h ultra-marathon race on clinical, laboratory and echocardiographic data.	Runners covered a mean distance covered of 140.3 ± 18.7 km.
Żebrowska et al. [34]	*N* = 14, Female = 0, Age 40.0 ± 11.7 yrs	Prospective	24-h ultra-marathon	Acute effects of a 24-h ultra-marathon on echocardiographic parameters and cardiac biomarkers.	Mean distance covered was 149.4 ± 33 km.
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	In total, mean distance of 168.5 ± 23.1 km was covered.
Wu et al. [36]	*N* = 11, Female = 1, Age 45.1 ± 2.6 yrs	Prospective	24-h ultra-marathon	Changes in hematological, hepatic biomarkers and parameters of iron metabolism in response to a 24-h ultra-marathon.	Mean distance of 158.6 ± 26.78 km was covered.
Hohl et al. [37]	*N* = 25, Age novice runners 43.1 ± 8.7 yrs, experienced runners 41.4 ± 9.1 yrs	Prospective	24-h ultra-marathon	Differences in biomarker changes after a 24-h ultra-marathon between novice and experienced ultra-runners.	Experienced runners ran significantly longer distances (158.8 ± 15.8 km) than novice runners (116.8 ± 10.3 km).

Table 1 (continued)

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Nicolas et al. [38]	*N* = 14, Female = 0, Age 43.8 ± 10.2 yrs	Prospective	24-h ultra-marathon	State of stress and recovery following a 24-h ultra-marathon. RESTQ-Sport	Runners covered a mean distance of 157.8 ± 37.5 km.
Chatzakis et al. [39]	*N* = 283, Female = 46	Field study	24-h ultra-marathon at International Ultramarathon Festival held in Athens-Hellinikon, Greece	To examine the effect of sex and performance standard on pacing profiles in a 24hultra-marathonrace	Mean distance ran was 159.99 ± 36.04 km.

POMS Profile of Mood States, *RESTQ-Sport* Recovery Stress Questionnaire for Athletes

Table 2 Sex differences in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Knechtle et al. [17]	*N* = 27,430, Female = 5,952	Retrospective	6-h, 12-h, 24-h, 48-h, 72-h, 144-h, and 240-h ultra-marathon	Sex differences in different time-limited ultra-marathons between 1975–2013.	The sex gap increased for all races with increasing age of athletes. The gap between women and men increased in 24-h and 48-h, but decreased in 6-h, 72-h, 144-h, and 240-h. In older age groups, a higher men-to-women ratio was observed. In all ultra-marathon durations, the participation of female and male runners varied significantly by age.
Peter et al. [19]	*N* = 34,049, Female = 6,463	Retrospective	24-h ultra-marathon	Sex differences regarding 24-h ultra-marathon performance between 1977–2012.	Comparing running speed between women and men in top 10 ever, top 100 ever and all finishers, men ran significantly faster by 12.9 ± 0.8%, 12.2 ± 0.4%, and 4.6 ± 0.5%, respectively.
Sousa et al. [41]	*N* = 414, Female = 200	Retrospective	5-km, 8-km, 10-km, 10-miles, 20-km, half-marathon, 25-km, 30-km, marathon, 50-km, 50-miles, 100-km, 100-miles, 12-h, 24-h, 48-h, and 144-h ultra-marathon	Sex differences in performance of American master road runners from 5-km race to 144-h ultra-marathon in participants aged between 40–99 yrs.	Performance gap between female and male athletes showed higher effects in athletes aged 85 yrs or above. Lower effects in performance gap between women and men were found for ages 40–54 yrs.
Thuany et al. [16]	*N* = 210,455, Female = 52,291	Retrospective	12-h and 24-h ultra-marathon	Differences in participation, sex, and age of peak performance in 12-h and 24-h ultra-marathon participants between 1876–2020	An increase in participation and a decrease in running speed was observed. Sex differences in terms of performance decreased over time. Male runners were faster than female runners. Oldest male athletes participated in 24-h (46.13 ± 10.83 yrs). Youngest female athletes participated in 12-h (43.46 ± 10.16 yrs). Age of peak performance was 41–50 yrs for both sexes.

and participation trends differ across various race distances and age groups. When ultra-marathons lasting from 6 h to 10 days (i.e. 6 h, 12 h, 24 h, 48 h, 72 h, 144 h, and 240 h) were analyzed, the gap between women and men decreased in 6, 72, 144 and 240 h, but increased in 24 and 48 h [17].

Changes Over Time in Sex Differences

Over the decades, women have been able to narrow the sex gap versus men in 24-hour ultra-marathon running [16, 19]. However, a study investigating all time-limited ultra-marathons showed that women were unable to narrow the gap versus men in 24-hour ultra-marathons [17]. Across calendar years, the gap between women and men increased in 24 h races from 0.2% in 1997 to 14.5% in 2017 [17]. These results indicate that while men still achieve greater distances in 24-hour ultra-marathon events, the performance gap between the sexes has narrowed over time. The varied findings may, however, be attributed to the differing timeframes and sample sizes.

Age of Peak Performance

The age of peak performance holds significant practical implications, as understanding it helps athletes establish optimal long-term training goals. Table 3 summarizes the findings from studies regarding the age of peak 24-hour ultra-marathon performance. Age appears to be a factor in ultra-marathon running performance. Research has

Table 3 Age of peak performance in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Knechtle et al. [18]	*N* = 31,588, Female = 6,863	Retrospective	6-h, 12-h, 24-h, 48-h, 72-h, 144-h, and 240-h ultra-marathon	Age-related performance differences in time-limited ultra-marathon races between 1975–2013.	The ages of peak performance are 33.7 yrs (95% CI 32.5–34.9 yrs) for 6-h, 39.4 yrs (95% CI 38.9–39.9 yrs) for 12-h, 43.5 yrs (95% CI 43.1–43.9 yrs) for 24-h, 46.8 yrs (95% CI 46.1–47.5 yrs) for 48-h, 43.6 yrs (95% CI 40.9–46.3 yrs) for 72-h, 44.8 yrs (95% CI 43.9–45.7 yrs) for 144-h, and 44.6 yrs (95% CI 42.9–46.3 yrs) for 240-h ultra-marathon. The peak of age in 48 h was significantly higher compared to 6 h. The age of peak performance was lower in 72 h than in 48 h. With increasing ultra-marathon finishes, runners had better performances.
Peter et al. [19]	*N* = 34,049, Female = 6,463	Retrospective	24-h ultra-marathon	Sex differences regarding 24-h ultra-marathon performance between 1977–2012.	Age of peak running speed increased for the annual fastest men from 23 yrs (1977) to 53 yrs (2012), but remained unchanged in the annual 10 and 100 fastest men at 40.9 ± 2.5 yrs and 44.4 ± 1.1 yrs, respectively. Age of peak running speed for the annual fastest (43.0 ± 6.1 yrs), annual 10 fastest (43.2 ± 2.6 yrs), and annual 100 fastest women (43.8 ± 0.8 yrs) did not change over time.
Rüst et al. [20]	*N* = 79,850, Female = 16,399	Retrospective	6-h, 12-h, 24-h, 48-h, 72-h, 144-h, 240-h ultra-marathon	Sex differences in age of peak performance of different time-limited ultra-marathon races.	The fastest ten women ever in 6-h, 12-h, 24-h, 48-h, 72-h, 144-h, and 240-h were 41 ± 9, 41 ± 6, 42 ± 5, 46 ± 5, 44 ± 6, 42 ± 4, and 37 ± 4 yrs old. In men, ages for the 10 fastest were 35 ± 6, 37 ± 9, 39 ± 8, 44 ± 7, 48 ± 3, 48 ± 8 and 48 ± 6 yrs, respectively. Age of peak performance in ultra-marathon athletes did not increase with increasing race duration.
Thuany et al. [16]	*N* = 210,455, Female = 52,291	Retrospective	12-h and 24-h ultra-marathon	Differences in participation, sex, and age of peak performance in 12-h and 24-h ultra-marathon participants between 1876–2020.	Oldest male athletes participated in 24-h (46.13 ± 10.83 yrs). Youngest female athletes participated in 12-h (43.46 ± 10.16 yrs). Age of peak performance was 41–50 yrs for both sexes.
Zingg et al. [15]	*N* = 39,664, Female = 8,013	Retrospective	24-h ultra-marathon	Changes in running speed and age of peak running speed in elite 24-h ultra-marathoners between 1998–2011.	Age of annual fastest woman decreased from 48 yrs to 35 yrs over the study period, whereas in men it remained unchanged at 42.5 ± 5.2 yrs. Age of annual top 10 women decreased from 42.6 ± 5.9 yrs (1998) to 40.1 ± 7.0 yrs was observed, but remained unchanged in men at 42 ± 2 yrs. Running speed in annual fastest men and women remained unchanged at 11.4 ± 0.4 km/h and 10.0 ± 0.2 km/h, respectively. Running speed in annual ten fastest women increased from 9.3 ± 0.3 to 9.6 ± 0.3 km/h, and no changes in annual top 10 men were observed.

shown that the age at which peak ultra-marathon performance occurs increases with longer race durations and a greater number of finishes [18]. For ultra-marathon runners who participated in time-limited ultra-marathons, race performance improved as the number of finishes increased [18].

Several studies have examined the age of peak performance in 24-hour running [15, 16, 18–20]. Generally, the best performances in this race format were achieved between the ages of 40 and 50 years [15, 16, 20].

Variables Influencing Performance

Different variables seem to predict 24-hour ultra-marathon performance (Table 4). Several potential predictive variables were examined for optimal performance in a 24-hour ultra-marathon [26–29, 31, 42, 43]. A combination of physiological, psychological, and strategic factors influences performance in 24-hour ultra-marathons. Key determinants include training volume and intensity, pacing strategy, nutritional intake, psychological factors, physiological factors, experience, and previous performance. The 'big three' strategies of training, nutrition, and pacing are of importance for optimal performance.

Consistent high-volume training is crucial for success in ultra-marathons. A case study of a 32-year-old

Table 4 Performance-related variables

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Takayama et al. [42]	*N* = 9, Female = 4, Age 42.14 ± 9.56 yrs	Cross-sectional	24-h ultra-marathon	Performance related variables in 24-h ultra-marathon in experienced ultra-runners.	Male runners had significantly less BF percentage and higher VO_2max values compared to female counterparts. VO_2max correlated significantly to mean running speed, but not total distance covered. Running speed at 2.67 and 3.56 m s^{-1} was positively associated with total distance covered.
Knechtle et al. [26]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Descriptive field study	24-h ultra-marathon	Influence of anthropometry, training, and prior marathon performance on 24-h ultra-marathon performance.	No significant correlation between age, BM, height, length of lower limbs, skin-fold thicknesses, circumference of extremities, SMM, BF percentage, and total distance covered was found. No significant association was present between total reached distance and weekly training hours, running yrs, number of finished marathons, and 24-h ultra-marathons. Total covered distance in 24-h ultra-marathon race was significantly and positively associated with personal best marathon performance and personal best 24-h ultra-marathon distance.
Knechtle et al. [27]	*N* = 22, Female = 0, Age 45.9 ± 6.6 yrs	Cross-sectional	24-h ultra-marathon	Association between skin-fold thickness and training characteristics with 24-h ultra-marathon performance.	No association between race performance and skin-fold thickness at various sites (pectoralis, axilla, triceps, subscapular, abdominal, suprailiac, thigh, and calf), and weekly training hours or mileage. Skin-fold thickness did not correlate with training volume or speed in running training.
Knechtle et al. [28]	*N* = 63, Female = 0, Age 46.9 ± 10.3 yrs	Retrospective	24-h ultra-marathon	Relation between anthropometric and training characteristics with 24-h ultra-marathon performance.	BM, the sum of nine skinfolds, sum of upper body skinfolds, and BF percentage correlated negatively with race performance. Weekly training mileage, longest training session before the 24-h run correlated inversely, and personal marathon record was positively associated with 24-h performance. Best correlation with race performance was longest training session before the 24-h race and personal best marathon time.
Knechtle et al. [31]	*N* = 63, Female = 0, Age 46.9 ± 10.3 yrs	Retrospective	24-h ultra-marathon	Association between leg skinfold thickness and 24-h ultra-marathon race performance.	BM, skinfold thickness at various sites (axilla, subscapular, abdomen, suprailiac), the sum of skinfold thickness, percentage BF, weekly training mileage, personal best marathon and 100-km ultra-marathon time were related to 24-h race performance. In multivariate analysis, no anthropometric or training variable correlated with 24-h performance.
Millet et al. [29]	*N* = 14, Female = 0, Age 41.1 ± 8.9 yrs	Prospective	24-h treadmill ultra-marathon	Physiological performance-related factors in 24-h ultra-marathon. Muscle biopsy	Race performance correlated significantly with VO_2max. VO_2max was significantly related with a higher capillary tortuosity. Specific endurance was significantly associated with running economy and citrate synthase activity.
Warren et al. [43]	*N* = 10, Female = 1, Age 40.1 (range 31–53) yrs	Prospective	24-h ultra-marathon	Effects of ventilatory muscle fatigue on 24-h ultra-marathon performance.	After correction for between-subject differences in running speed maximum voluntary ventilation for 12 s explained 39% of variance in running speed, suggesting a potential influence on ultra-marathon performance.

BF body fat, *BM* body mass, *SMM* skeletal muscle mass, *VO_2max* maximal oxygen uptake

male ultra-marathon runner highlighted the importance of structured training in preparing for 24-hour events [44]. Also, proper nutrition during the race is essential to maintain energy levels and prevent fatigue [42, 44]. However, other variables such as body fat [42], running economy [29, 42], maximum oxygen uptake (VO_2max) [29, 40, 42] and lung function [43] were also linked to 24-hour running performance. Limited information has been provided regarding the significance of certain physiological variables [40, 42]. VO_2max showed a significant correlation with mean running speed, but not with the distance covered [42]. A recent study found that higher pre-race levels of hematocrit, lactate dehydrogenase (LDH), total cholesterol, high-density lipoprotein (HDL) cholesterol/

low-density lipoprotein (LDL) cholesterol ratio, and triglycerides, along with lower levels of monocytes, eosinophils, alanine aminotransferase (ALT), gamma-glutamyl transferase (GGT), total proteins, and sodium, were linked to increased race distance [45].

Anthropometric Characteristics

Table 4 provides a summary of the anthropometric characteristics reported for 24-hour ultra-marathon runners that may have a potential influence on race performance [26–29, 31, 42, 43]. These anthropometric characteristics including body mass [26, 28, 31], body height [26], lower limb length [26], skinfold thicknesses [26–28, 31], limb circumference [26], skeletal muscle mass [26], and percent body fat [26, 28, 31] did not appear to have an effect on 24-hour running performance.

Training Variables

Along with the anthropometric characteristics noted for 24-hour ultra-marathon runners, Table 4 summarizes training aspects such as weekly training volume in hours or weekly running kilometers [26–29, 31, 42, 43]. Training in the preparation for a 24-hour ultra-marathon appears to be crucial [46]. The analysis of a world-class 24-hour ultra-marathon runner's training showed that ultra-marathon training needs to incorporate a high volume of running at various paces and intensities, along with cross-training [46]. Pre-race, the athlete completed five training blocks, with a running volume per training block from 172 km to 263 km per week. Peak running volume per training block was on average 3.2 weeks out from a race and reached a maximum of 378 km per week [46].

However, training characteristics seemed to have little predictive value, as factors like weekly training volume in hours [26, 31], weekly running kilometers [31] and running speed during training [27, 31] were not related to race performance. In other instances, however, weekly kilometers run [28] and the longest training session before the 24-hour race [28] were meaningful. Most likely, the statistical approach and the sample size play a role in determining whether a variable has predictive power. In the mentioned studies, both anthropometric and training characteristics from specific 24-hour ultra-marathons were bi- and multi-variately analyzed regarding a potential association with race performance [26–28, 31].

Previous Experience

Table 4 summarizes aspects of prior experience along with the anthropometric characteristics and training variables reported for 24-hour ultra-marathon runners [26–29, 31, 42, 43]. Previous experience including the runner's best personal marathon time [26, 28], the longest training run before the race [28] and the best personal performance in 24-hour ultra-marathon running [26] were shown to be related to race performance. However, years of running [26], the number of finished marathons [26] and the number of finished 24-hour ultra-marathons [26] were not predictive. To cover the greatest possible distance in a 24-hour ultra-marathon, runners need to have a personal best marathon time of around 3 h and 20 min and complete a long training run of at least 60 km before the race [28].

Experienced ultra-marathon runners often demonstrate better pacing strategies, which are essential for optimal performance in a 24-hour race. A case study emphasized the significance of the 'big three' strategies—training, nutrition, and pacing—in affecting ultra-marathon performance [44]. Ultra-marathoners usually run higher weekly mileage at lower intensities than marathoners [3]. This training method can improve their endurance, and making them more equipped to handle the extended demands of races [10].

Success in ultra-marathons is often related to psychological factors such as mental toughness, self-efficacy, and emotional intelligence [3, 47]. Experienced runners may develop cognitive strategies to maintain mood stability, which is crucial during the mental and physical challenges of a race [47]. Experienced runners often develop effective injury prevention and management strategies through their training and racing history [48].

Pacing During the Race

Pacing refers to the regulation of physical performance and the distribution of effort during a sports competition [49]. Table 5 presents a summary of the findings on pacing for 24-hour ultra-marathon runners [2, 22, 25, 39, 50]. Effective pacing in an ultra-marathon is crucial for achieving optimal performance [2, 22, 39, 44, 50]. Variables influencing pacing are sex [2, 22, 50], age [22, 50] and performance level [2, 22, 25, 39, 50].

Different pacing behaviors have been described, such as a J-shaped pattern [22] or a reverse J-shaped pattern [39, 50], depending on whether the distance covered or the running speed was used to draft the curve. Variable pacing has also been described [2]. Runners tend to aim for the highest distance in the first part of the race. A study involving 283 participants in the International Ultramarathon Festival held in Athens-Hellinikon, Greece found that ~ 60% of the total distance was covered in the first 12 h, with one-third of the distance completed in the first 6 h [39]. In addition, proper nutrition and hydration are essential for maintaining energy levels and avoiding disruptions in pacing [44].

Table 5 Pacing in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Bossi et al. [22]	*N* = 501, Female = 103	Retrospective	24-h ultra-marathon	Different pacing strategies in a 24-h ultra-marathon.	Pacing data showed a reversed J-shape with a significant reduction in pace from in the second-to-last to the last race hour. Significant correlation between race time and performance groups were observed. No correlation between race time and sex or age group.
Chatzakis et al. [39]	*N* = 283, Female = 46, Age range 24–71 yrs	Retrospective	24-h ultra-marathon	Influence of performance level and sex on pacing in 24-h ultra-marathon.	Pacing followed the shape of a reverse J-curve. Significant association between performance standard was found where better runners showed more even pacing. No relation between pacing and sex. CV was inversely related with total distance covered and total running time.
Deusch et al. [2]	*N* = 937, Female = 260, Age 48.62 ± 11.8 yrs	Retrospective	6-h, 12-h, and 24-h ultra-marathon	Differences in age, sex, and performance level in time-limited ultra-marathoners.	More male runners participated in the longer races compared to shorter ones. Men were older and had shorter race times compared to women. Comparing the three race durations, fastest runners were in 6-h, the oldest runners were in 12-h, and 24-h runners showed the most variable pacing. In 12-h and 24-h, faster running speed correlated significantly with less variable pacing.
Lavoué et al. [50]	*N* = 51, Female = 21, % in age group 31–35 yrs (14%), 36–40 yrs (20%), 41–45 yrs (14%), 46–50 yrs (10%), 51–55 yrs (16%), 56–60 yrs (12%), 61–65 yrs (4%) and 66–70 yrs (12%)	Prospective	24-h ultra-marathon	Differences in pacing between sex and performance level during a 24-h ultra-marathon.	Runners showed a reverse J-curve pacing behavior. Male and high-performance runners had significantly higher mean speed during the competition and spent less time at substantial speed reductions compared to female and low-performance runners. Total covered distance was negatively associated with the number of substantial speed reductions and speed CV in both male and female runners.
Takayama et al. [25]	*N* = 48, Female = 0	Prospective	24-h ultra-marathon	Influence of pacing on 24-h ultra-marathon performance in different performance groups.	Ten fastest runners (Group A) covered a mean distance of 236.38 ± 11.41 km whereas 40th -48th fastest runners (Group E) covered a mean of 164.14 ± 2.49 km. Group A showed a mean CV of 14.3 ± 4.3% whereas group E had a CV of 45.0 ± 16.6%. CV was negatively associated with total distance covered.

CV coefficient of variation

The Performance Level Aspect of Pacing The performance level aspect of pacing seems to be of considerable importance compared to sex or age [22, 39]. Faster runners started at lower relative intensities [22] and displayed a more even pacing strategy than slower runners [22, 39]. In addition, faster runners maintained a more consistent running pace than slower runners and exhibited less speed variability [39]. The fastest runners showed less substantial running speed reductions [50] and maintained a higher mean running speed with fewer speed variations throughout the race [25, 50].

The Sex Aspect of Pacing Sex appears to have various effects on the pacing of 24-hour ultra-marathon runners [22, 39, 50]. Men showed a higher mean running speed with less variation throughout the race compared to women [50]. However, in some studies, sex showed no influence on the pacing strategy [22, 39].

The Age Aspect of Pacing Little is known regarding the aspect of age, but age does not seem to significantly influence pacing in 24-hour ultra-marathon runners [22].

Nutrition, Fluid Metabolism and Energy Balance

Nutrition, including food and fluid intake, is a crucial aspect of ultra-marathon running performance [23, 51–58]. Table 6 summarizes the findings on this topic [23, 51–57]. Overall, a 24-hour run leads to an energy deficit [53, 57]. Research indicates that performance in a 24-hour ultra-marathon is positively correlated with

Table 6 Food and fluid intake in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Knechtle et al. [51]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Prospective	24-h ultra-marathon	Dehydration in 24-h ultra-runners.	BM decreased significantly by 2.2 kg (95% CI, -3.3 to -1.2) and FM by 0.5 kg (95% CI, -0.8 to -0.1), the decrease in SMM failed to reach statistical significance. Decrease in BM correlated significantly with the decrease in FM. Total fluid intake was 15.1 L (95% CI 12.3–17.9) corresponding to 0.62 L/h (95% CI, 0.51–0.75). Fluid intake correlated significantly and negatively with average running speed.
Lavoué et al. [52]	*N* = 12, Female = 6, Age 46 ± 7 yrs	Prospective	24-h ultra-marathon	Food and fluid consumption during a 24-h ultra-marathon in elite athletes.	Mean fluid intake was 16.4 ± 6.9 L, corresponding to 0.69 ± 0.29 L/h. Mean EI was 35.1 ± 15.7 MJ, EB was mainly negative − 29.5 ± 16.1 MJ. 75% of athletes reported symptoms of GIS distress with nausea being the most frequent one. No runner developed EAH. Race performance was significantly associated with EI and negatively with fluid intake.
Chlíbková et al. [53]	*N* = 14, Female = 6, Age male runners 30.0 ± 10.7 yrs, female runners 37.5 ± 12.9 yrs	Prospective	24-h winter ultra-marathon (average − 14.3 °C)	Hydration status after a 24-h ultra-marathon under extreme cold weather conditions.	BM decreased significantly post-race, but change in BM was not related to plasma $[Na]^+$. No runners developed EAH after the race. Average fluid intake was 0.3 L/h for female and 0.46 L/h for male runners, respectively. Post-race plasma $[Na]^+$ and BM was not related to fluid intake. Number of completed ultra-marathons and training kilometers correlated negatively to fluid intake.
Knechtle et al. [54]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Observational field study	24-h ultra-marathon	EAH prevalence in a 24-h ultra-marathon race.	No finisher developed EAH, and plasma $[Na]^+$ did not change significantly post-race. Total fluid intake was 15.1 L (95% CI 12.3–17.9) corresponding to 0.62 L/h (95% CI, 0.51–0.75), which correlated significantly with mean running speed. BM decreased significantly by 2.2 kg (95% CI, -3.3 to -1.2) and FM by 0.5 kg (95% CI, -0.8 to -0.1). BM change did not correlate with post-race plasma $[Na]^+$. PV increased by 4.9%
Costa et al. [55]	*N* = 25, Female = 6, Age 39 ± 7 yrs	Prospective	24-h ultra-marathon	Energy balance and hydration status during a 24-h ultra-marathon.	Total EI was 20 ± 7 MJ, total EE was 55 ± 11 MJ. CHO intake was 37 ± 24 g/h. Total fluid intake was 9.1 ± 4.0 L, corresponding to a rate of 0.38 ± 0.16 L/h. Significant decrease in BM with 1.6 ± 2.0%. Urinary ketones were present in 90% of runners after the race.
Gill et al. [56]	*N* = 36, Female = 17, Age runners 39 ± 7 yrs, control group 32 ± 11 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on salivary antimicrobial protein response and URTIs.	BM decreased significantly by 1.6 ± 2.0%, total fluid intake was 9.1 ± 4.0 L corresponding to 0.34 ± 0.16 L/h.
Linderman et al. [57]	*N* = 1	Case study	24-hour treadmill run	Assessment of energy expenditure (EE) and energy intake (EI)	Total EE estimated from HR telemetry and a metabolic equation was 12,820 and 12,425 kcals, respectively. Total EI of 4590 kcal came almost exclusively from CHO. Blood glucose ranged between 8.2 and 4.1 mmol/L, averaging 5.6 ± 1.1 mmol/L. Estimated lipid oxidation accounted for 5,000 kcals, and oxidation of CHO accounted for 1,900 kcal.
Charlot et al. [23]	*N* = 12, Female = 6, age: 46 ± 7 yrs, height: 170 ± 9 cm, weight: 61.1 ± 9.6 kg	Prospective	24-h run World Championship	Investigation of the fluctuations of food and fluid intake during the 24-h run World Championship of 12 elite athletes	Water, total fluid, CHO, and EI decreased during the last quarter of the race relative to the first half. The differences were no longer significant after these values were normalized by the number of passages in front of the supply tent. Participants progressively failed to follow their nutritional program, with the intake of their planned items dropping to ~ 50% during the last quarter. This was compensated by increases in unplanned foods allowing them to match their expected targets. GIS, lack of appeal of the planned items, and attractivity of unplanned items explained their deviation from the program.

BM body mass, *CHO* carbohydrate, *EAH* exercise-associated hyponatremia, *EB* energy balance, *EE* energy expenditure, *EI* energy intake, *FM* fat mass, *GIS* gastrointestinal symptoms, *HR* heart rate, *kcal* kilocalorie, *MJ* Megajoule, *PV* plasma volume, *SMM* skeletal muscle mass energy intake and negatively correlated with fluid intake [53]. Fluid intake is essential to prevent dehydration [51, 59]. However, excessive fluid intake can lead to fluid overload [52] and exercise-associated hyponatremia (EAH) [60]. The findings underscore the importance of monitoring sodium levels to prevent EAH during prolonged physical activity. A 24-hour ultra-marathon promotes fluid conservation, where the observed post-race hypervolemia resulted from a renal response characterized by increased levels of aldosterone, cortisol, and antidiuretic hormone (ADH), while atrial natriuretic peptide (ANP) decreased [61].

Nutrition Before the Race There have been few reports on pre-race nutrition for this specific race format. Pre-race carbohydrate intake needs to be high at ~7 g/kg of body weight per day [44].

Nutrition During the Race Energy intake during a 24-hour race must be high at ~ 35.1 ± 15.7 MJ [52]. In general, 24-hour ultra-marathon runners consume carbohydrates [52, 57]. Carbohydrate intake during the race needs to be high at ~ 1.49 ± 0.71 kg [52] with hourly intakes of ~ 48 g [44]. Fortunately, high intakes of carbohydrates were not associated with gastrointestinal discomfort [52]. During a 24-hour ultra-marathon, runners progressively failed to adhere to their nutritional program, with the intake of their planned items dropping to ~ 50% in the last quarter [23]. However, despite clear challenges in following their nutritional programs largely due to gastrointestinal issues, the 24-hour ultra-marathon runners were able to sustain high fluid and food intake during the race, thus achieving their planned elevated nutritional goals [23].

Nutrition After the Race We found no studies on nutrition following a 24-hour ultra-marathon to enhance recovery. Future research may address this scientific gap.

Fluid Intake During a 24-Hour Ultra-Marathon

Fluid intake during a race is crucial, as research has shown that it negatively impacts race performance [52]. Table 6 summarizes the findings on this topic. The total fluid intake during a 24-hour run was reported to be ~ 15.1 ± 5.1 L [54] to ~ 16.4 ± 6.9 L [52], which corresponds to an hourly consumption of ~ 0.62 ± 0.21 L [54] to ~ 0.69 ± 0.29 L [52]. However, lower values of ~ 9.1 ± 4.0 L have also been described, corresponding to an hourly intake rate of ~ 0.38 ± 0.16 L [55]. Regarding hydration, an hourly fluid intake of 0.30 ± 0.06 L was reported for female and 0.46 ± 0.21 L for male 24-hour ultra-marathoners, with no significant differences between the sexes [53]. One study examined the hydration status of 20 runners during a 24-hour race at an average temperature of -14.3 °C, and the results indicated that hydration remained stable despite extreme conditions, suggesting that overall fluid intake was likely adequate for the runners' needs [53]. Fluid intake seemed to be dependent upon running speed [54] and experience where 24-hour ultra-marathon runners with a higher number of completed ultra-marathons and a higher number of training kilometers drank less than those with less running experience [53]. These studies contribute to a better understanding of athletes' nutritional strategies and physiological responses during 24-hour endurance races.

Exercise-Associated Hyponatremia in 24-Hour Ultra-Marathon Running

Closely related to fluid metabolism is the appearance of exercise-associated hyponatremia (EAH) due to overdrinking [62]. Table 7 summarizes the findings on this topic [35, 52–54, 60]. The prevalence of EAH in 24-hour ultra-marathon runners is relatively low [63], ranging from 0% [52–54] to 8.3% [60]. Risk factors for female 24-hour ultra-marathon runners appear to include age, extensive race experience in this discipline, strong race performance, weekly training hours, and the occurrence of the luteal phase of the menstrual cycle during the race [63].

Change in Body Mass

Generally, a 24-hour ultra-marathon results in a reduction in body mass [51, 54, 55, 59, 60, 64]. Table 8 summarizes the findings on this topic [33, 51, 54, 55, 59, 64–66]. The decrease in body mass varies from ~ 2 kg [51] to ~ 4.4 ± 1.1 kg [66], which corresponds to a change in body weight of ~ 5% [59]. The decrease in body mass appears to depend on running speed, with the most significant reduction occurring during the first 4 to 8 h of the race [59]. Body mass remained relatively stable after 8 h of running, although a further decrease was noticeable between 16 and 20 h of running during the 24-hour race [59].

The reduction in body mass during a 24-hour ultra-marathon may result from a decrease in skeletal muscle mass or a loss of fat mass [67, 68]. It has been shown that a 24-hour ultra-marathon led to a decrease in skeletal muscle mass, with the decrease in muscle mass being associated with a decrease in body mass [64]. A decrease in body mass may also correlate with a decrease in fat mass [51, 67, 68], with the fat loss appearing to derive mainly from visceral fat [67].

Regarding the decrease in body mass, there appeared to be differences between female and male runners [64]. In male 24-hour ultra-marathon runners, both body mass and body fat decreased, while skeletal muscle mass remained stable. In female runners, however, body fat

Table 7 Exercise-associated hyponatremia in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Chlíbková et al. [60]	*N* = 58, Age ultra-mountain bike group I 40.3 ± 9.1 yrs, ultra-mountain bike group II 36.8 ± 6.4, ultra-marathon group 38.3 ± 7.7, multi-stage ultra-mountain bike group 38.0 ± 6.1 yrs	Prospective	24-h ultra-mountain bike race (R1, R2), 24-h ultra-marathon (R3), multi-stage ultra-mountain bike race (R4)	Prevalence of EAH in different 24-h ultra-races.	5.7% of finishers developed EAH (3.7% of ultra-mountain bikers, 8.3% ultra-runners, and 7.1% multi-staged mountain bikers). Plasma $[Na]^+$ significantly decreased only in R4. BM decreased in all races. Change in BM and percent change in BM were significantly positively related to lower-post-race $[Na]^+$ levels in R3. Post-race plasma $[Na]^+$ correlated negatively with race performance in R2 and R3, finishers with more kilometers had lower plasma $[Na]^+$
Chlíbková et al. [53]	*N* = 14, Female = 6, Age male runners 30.0 ± 10.7 yrs, female runners 37.5 ± 12.9 yrs	Prospective	24-h winter ultra-marathon (average − 14.3 °C)	Hydration status after a 24-h ultra-marathon under extreme cold weather conditions.	BM decreased significantly post-race, but change in BM was not related to plasma $[Na]^+$. No runners developed EAH after the race. Average fluid intake was 0.3 L/h for female and 0.46 L/h for male runners, respectively. Post-race plasma $[Na]^+$ and BM was not related to fluid intake. Number of completed ultra-marathons and training kilometers correlated negatively to fluid intake.
Knechtle et al. [54]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Observational field study	24-h ultra-marathon	EAH prevalence in a 24-h ultra-marathon race.	No finisher developed EAH, and plasma $[Na]^+$ did not change significantly post-race. Total fluid intake was 15.1 L (95% CI 12.3–17.9) corresponding to 0.62 L/h (95% CI, 0.51–0.75), which correlated significantly with mean running speed. BM decreased significantly by 2.2 kg (95% CI, -3.3 to -1.2); BM change did not correlate with post-race plasma $[Na]^+$. PV increased by 4.9%
Lavoué et al. [52]	*N* = 12, Female = 6, Age 46 ± 7 yrs	Prospective	24-h ultra-marathon	Food and fluid consumption during a 24-h ultra-marathon in elite athletes.	Mean fluid intake was 16.4 ± 6.9 L, corresponding to 0.69 ± 0.29 L/h. Mean energy intake was 35.1 ± 15.7 MJ, energy balanced was mainly negative − 29.5 ± 16.1 MJ. 75% of athletes reported symptoms of GI distress with nausea being the most frequent one. No runner developed EAH. Race performance was associated with energy intake and with fluid intake.
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	No significant changes in serum $[Na]^+$ were observed.

BM body mass, *EAH* exercise-associated hyponatremia, *GI* gastrointestinal, *MJ* Mega joule, *PV* plasma volume, *R* race

decreased, whereas both body mass and skeletal muscle mass remained stable [65].

Effects on Systems

The effects of running a 24-hour ultra-marathon have been investigated on various systems, including the cardiovascular system (Table 9), the kidneys (Table 10), the gastrointestinal system (Table 11), the immune system (Table 12), and the hematological system (Table 13). A 24-hour ultra-marathon leads to specific changes in selected laboratory values. Significant changes occur in muscle metabolism, liver function, kidney function, and hemolysis, with most alterations happening during and 24 h after the race [69].

Effects on the Cardiovascular System

The cardiovascular system, consisting of the heart and blood vessels, supplies the entire body with blood [70], and the impact of various modes of exercise on this system has been well studied [71]. Several studies have investigated the influence of a 24-hour ultra-marathon on the cardiovascular system (Table 9) [30, 33–37, 71, 72]. Such a race leads to changes in blood pressure [30, 33, 66], changes in cardiovascular biomarkers such as creatine kinase (CK) [30, 33, 34, 37, 72–75], troponin [33, 34, 37, 72, 74, 75] and N-terminal pro-brain natriuretic peptide (NT-proBNP) [30, 33, 34, 37, 72, 74, 75] and a heart rate of 130–140 beats per minute during the race [73].

Changes in electrocardiography (ECG) [73, 76] and echocardiography [30, 33, 34, 73] have also been reported. In a study where ECG changes were found, the authors explored why such a race caused ECG changes,

Table 8 Body mass changes in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Chlíbková et al. [64]	*N* = 14, Female = 6, Age male runners 30.0 ± 10.7 yrs, female runners 37.5 ± 12.9 yrs	Prospective	24-h winter ultra-marathon (average − 14.3 °C)	Changes in body composition as well as biomarkers of skeletal and renal damage after a 24-h winter ultra-mountain marathon.	In men, BM and BF decreased [-1.1 kg (-1.4%) and − 1.1 kg (-13.4%), respectively]; SM and TBW remained stable. In women, BF decreased [-1.3 kg (-7.8%)], BM, SM and TBW remained stable. The change (Δ) in BM was not related to Δ BF; Δ BM was related to Δ SM and Δ TBW. Δ SM correlated with Δ TBW. Δ BF was negatively associated with Δ SM. The decrease in BM was negatively related to the increase in CK.
Costa et al. [55]	*N* = 25, Female = 6, Age 39 ± 7 yrs	Prospective	24-h ultra-marathon	Energy balance and hydration status during a 24-h ultra-marathon.	Significant decrease in BM by 1.6 ± 2.0%.
Kao et al. [59]	*N* = 52, Female = 5, Age 12-h runners 45.3 ± 6.4 yrs, 24-h runners 45.7 ± 8.5 yrs	Prospective	12-h and 24-h ultra-marathon	Changes in BM during a 12-h and 24-h ultra-marathon and impact on performance.	BM decreased significantly by -2.89 ± 1.56% in 12-h runners and by -5.05 ± 2.28% in 24-h runners. In 24-h finishers, 26% lost more than 7% of their pre-race BM. Greatest BM change occurred during the first 4 h in both races and BM remained relatively constant after 8 h with a further decrease between 16–20 h in 24-h ultra-marathon. In 24-h race, decrease of BM correlated significantly with performance (total distance covered).
Knechtle et al. [51]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Prospective	24-h ultra-marathon	Dehydration in 24-h ultra-runners.	BM decreased significantly by 2.2 kg (95% CI, -3.3 to -1.2) and FM by 0.5 kg (95% CI, -0.8 to -0.1), the decrease in SM failed to reach statistical significance. Decrease in BM correlated significantly with the decrease in FM.
Knechtle et al. [54]	*N* = 15, Female = 0, Age 46.7 ± 5.8 yrs	Observational field study	24-h ultra-marathon	EAH prevalence in a 24-h ultra-marathon race.	BM decreased significantly by 2.2 kg (95% CI, -3.3 to -1.2) and FM by 0.5 kg (95% CI, -0.8 to -0.1),
Passaglia et al. [33]	*N* = 20, Female = 0, Age 43.3 ± 9.9 yrs	Prospective	24-h ultra-marathon	Effects of a 24-h ultra-marathon race on clinical, laboratory and echocardiographic data.	Mean BM loss was 3.2%.
Gill et al. [65]	*N* = 17, Female = 3, Age 40 ± 7 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on cytokine profile as well as GI system.	BM decreased by 1.7 ± 1.8% after the race.
Gill et al. [56]	*N* = 36, Female = 17, Age runners 39 ± 7, control group 33 ± 11 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on salivary antimicrobial protein response and URTIs.	BM decreased significantly by 1.6 ± 2.0%,

BF body fat; *BM* body mass, *CK* creatine kinase, *EAH* exercise-associated hyponatremia, *GI* gastrointestinal, *SM* skeletal muscle mass, *TBW* total body water, *URTI* upper respiratory tract infection

noting that T waves on the anterior chest leads were significantly elevated after the race, as well as changes in echocardiography, indicating a reduced left ventricular performance following the race [73]. Interestingly, repolarization disorders emerged immediately after a 24-hour run, lasting up to 14 h post-effort [76].

However, all these changes generally returned to baseline within a few days after the race [30, 33, 34, 71]. In a study of elite 24-hour ultra-marathon runners, an almost 135-fold increase in total CK (from 447 U/L pre-race to 60,060 U/L post-race) was observed [73]. Although the MB fraction was also significantly elevated (11 to 1,680 U/L), the MB percentage of total CK remained within normal limits (≤ 4%) [73].

Effects on Renal Function

The renal system (i.e., the kidney, ureters, and urethra) filters toxins and metabolic waste products from the blood [77] and can be functionally and structurally damaged during ultra-endurance exercise [78]. AKI is frequently observed in ultra-runners [75]. Table 10 summarizes the

Table 9 Effects on the cardiovascular system

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Niemelä et al. [30]	*N* = 13, Female = 0, Age 38 ± 8 yrs	Prospective	24-h ultra-marathon	LV function after a 24-h ultra-marathon in experienced male ultra-marathoners.	CK and CK-MB increased significantly post-race (by 110.6-fold and 105.5-fold, respectively) and peaked at 27,427 U/l and 422 U/l immediately after the race. LVEDD was significantly reduced by 7%, while LVESD showed no changes. Stroke dimension decreased by 24% and fractional shortening by 16%. Reduction in fractional shortening correlated significantly with change in LVESD. Stroke dimension and ejection phase indexes returned to baseline levels within 2–3 post-race days.
Passaglia et al. [33]	*N* = 20, Female = 0, Age 43.3 ± 9.9 yrs	Prospective	24-h ultra-marathon	Effects of a 24-h ultra-marathon race on clinical, laboratory and echocardiographic data.	Immediately after the race, a significant decrease in systolic (by 1.2-fold) and diastolic blood pressure (by 1.1-fold) was observed, compared to pre-race values. Significant increase in urea (by 1.4-fold), creatinine (1.2-fold), CK-MB (by 35.9-fold), and WBC (by 7.1-fold) were observed, while potassium, and lymphocytes significantly decreased by 1.1-fold and 1.3-fold, respectively. Significant post-race increases in A as well E'/A' and a decrease in E/A was observed, no significant changes in LVEF were noted.
Żebrowska et al. [34]	*N* = 14, Female = 0, Age 40.0 ± 11.7 yrs	Prospective	24-h ultra-marathon	Acute effects of a 24-h ultra-marathon on echocardiographic parameters and cardiac biomarkers.	Echocardiographic parameters showed no significant changes 48-h post-race compared to baseline measures apart from E/A which decreased significantly by 1.5-fold post-race suggesting altered diastolic function. NT-proBNP levels increased significantly and reached peak values after 42.125 km into the race and decreased thereafter. Levels correlated with age as well as levels at 24-h were negatively associated with running distance. CK-MB increased constantly during the race and reached peak values immediately after the race. Values post-race correlated with LVESD. cTnT and hsCRP concentrations increased significantly during the race and reached peak levels at 24-h.
Niemelä et al. [71]	*N* = 12, well-trained runners	Prospective	24-h ultra-marathon	Effect of a competitive 24-h run on the left ventricular diastolic function	Mitral valve opening was delayed, early diastolic filling was decreased and prolonged, and posterior wall thinning was reduced, particularly among those athletes completing close to 200 km or more. The delay in mitral valve opening, the decrease in the peak rate of dimension increase, and the prolongation of the early diastolic filling period were correlated with the distance completed. The reductions in left ventricular end-diastolic dimension and fractional shortening were not in proportion to the distance run
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	Total cholesterol, LDL cholesterol, and TG decreased significantly 24-h after the race by 1.3-fold, 1.4-fold, and 2.2-fold, whereas HDL cholesterol and FFA increased 24-h post-race by 1.4-fold and 3.0-fold, respectively.
Wu et al. [36]	*N* = 11, Female = 1, Age 45.1 ± 2.6 yrs	Prospective	24-h ultra-marathon	Changes in hematological, hepatic biomarkers and parameters of iron metabolism in response to a 24-h ultra-marathon.	TG and LDL cholesterol decreased significantly directly after the race by 1.4-fold and 1.1-fold.

Table 9 (continued)

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Hohl et al. [37]	*N* = 25, Age novice 43.1 ± 8.7, experienced 41.4 ± 9.1 yrs	Prospective	24-h ultra-marathon	Differences in biomarker changes after a 24-h ultra-marathon between novice and experienced ultra-runners.	In the experienced groups, a significant time x performance level interaction with a more pronounced increase of cTnT, NT-proBNP, and cortisol.
Chalchat et al. [72]	*N* = 11	Prospective field study	24-h run World Championships	Acute response of skeletal/cardiac muscle and kidney biomarkers	High CK activity (53,239 ± 63.608 U/L) immediately after the race, and remained elevated 24 h after.

A atrial contraction mitral inflow velocity; *A'* late diastolic velocity of the mitral annulus, *CK* creatine kinase, *CK-MB* creatine kinase myocardial band, *CRP* C-reactive protein, *cTnT* cardiac troponin T, *E* early mitral inflow filling velocity, *E'* early diastolic velocity of the mitral annulus, *FFA* free fatty acids, *HDL* high density lipoprotein, *hsCRP* high-sensitivity C-reactive protein, *LDL* low density lipoprotein, *LV* left ventricle, *LVEDD* = left ventricular end-diastolic dimension, *LVEF* left ventricular ejection fraction, *LVESD* left ventricular end-systolic dimension, *NT-proBNP* N-terminal pro-brain natriuretic peptide, *TG* triglycerides, *WBC* white blood cells

findings on this topic [53, 55, 64, 66, 72, 75]. Running a 24-hour ultra-marathon leads to an impaired renal function [64, 75] with an increase in CK [63], an increase in plasma creatinine [64, 72, 75], an increase in urinary Na^+ [63], an increase in urinary post-race K^+/Na^+ ratio [63], an increase in urine specific gravity [51, 54], a decrease in glomerular filtration rate (GFR) [63] and a decrease in creatinine clearance [63, 64, 75]. These changes in renal function are most likely due to a combination of dehydration, protein catabolism, reduced excretion of osmotic agents, rhabdomyolysis, the renin-angiotensin-aldosterone system, and other factors [66]. To reduce the risk of AKI, any ultra-runner planning to compete in a 24-hour ultra-marathon needs to have a high skeletal muscle mass and engage in regular ultra-endurance training [75]. Fortunately, post-race renal function abnormalities in runners were resolved within 6–21 days after a 24-hour ultra-marathon [66].

Effects on the Gastrointestinal System

The gastrointestinal system, which includes the gastrointestinal tract and accessory organs, absorbs and digests food while eliminating waste products [79]. Some studies have investigated the effects of a 24-hour ultra-marathons on the gastrointestinal system [23, 35, 36, 52, 65]. Table 11 summarizes the findings on this topic [35, 36, 52, 65]. About two thirds of the runners complained of gastrointestinal discomfort [52, 65]. Markers of the gastrointestinal system, including total bilirubin (BIL-T), direct bilirubin (BIL-D), alkaline phosphatase (ALP), aspartate aminotransferase (AST), alanine aminotransferase (ALT), and lactate dehydrogenase (LDH), increased during the race [35, 36]. In absolute values, AST increased from 28.7 ± 7.7 U/L pre-race to 388.5 ± 295.8 U/L 24 h after the race, and ALT from 24.1 ± 6.4 U/L to 84.4 ± 50.7 U/L whereas y-GT remained unchanged [35]. In another study, AST increased from 37.10 ± 19.10 U/L pre-race to 536.70 ± 311.10 U/L immediately post-race, ALT from 35.10 ± 13.10 U/L to 118.40 ± 75.10 U/L, and LDH from 367.50 ± 105.60 U/L to 1420.50 ± 598.50 U/L whereas y-GT remained unchanged [36]. Interestingly, the changes in IL-10 and interleukin (IL)-8 were positively correlated with gastrointestinal symptoms [65].

Effects on the Immune System

The immune system protects against harmful agents [80]; however, its normal function may be affected by exercise [81]. Prolonged ultra-endurance exercise, such as a 24-hour ultra-marathon, triggers immune and inflammatory responses [24, 35, 74, 82]. A few studies have investigated the effects of such a race on the immune system [56, 65, 74, 82]. Table 12 summarizes the findings on this topic [35, 37, 56, 65, 82]. Such a race leads to an increase in C-reactive protein (CRP)/hs (high-sensitivity) CRP (hsCRP) [24, 35, 65, 74], endotoxin [65], IL-6 [35, 65, 74], IL-1β [65], tumor necrosis factor (TNF)-α [65], IL-10 [65] and IL-8 [65]. In addition, a 24-hour race can lead to a decrease in salivary flow rate [56], salivary immunoglobulin A [56], and lysozyme secretion rates [56].

Research indicated that participants experienced increased levels of circulatory endotoxins and pro-inflammatory cytokines after a 24-hour ultra-marathon [65]. Changes in immunological parameters among ultra-marathoners are influenced by the duration of the exertion [83]. The findings indicate that prolonged exercise may result in alterations to immune cell counts and their function [83]. Recent research found that ultra-endurance events induce changes in T-cells during the 48-hour recovery period, including an increase in T-cells that regulate the immune response and a decrease in pro-inflammatory cytokines. These findings indicate a complex immune response to prolonged endurance exercise [84]. Although such a race leads to the specific changes in immune system laboratory values mentioned above [56,

Table 10 Effects on kidney function

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Costa et al. [55]	*N* = 25, Female = 6, Age 39 ± 7 yrs	Prospective	24-h ultra-marathon	Energy balance and hydration status during a 24-h ultra-marathon.	Urinary ketones were present in 90% of runners after the race. No significant changes in POsmol values were observed at pre- to post-competition time points in the UER and were lower than those recorded in the CON group. Plasma volume increased at post-competition time points in the UER
Hsu et al. [75]	*N* = 22, Female = 1, Age 44 (range 28–67) yrs	Prospective	24-h ultra-marathon	Prediction model for AKI in 24-h ultra-marathon runners.	After the race, 45% of runners developed AKI Stage I. Significant post-race elevations of blood urea nitrogen (by 1.7-fold), creatinine (by 1.3-fold), CK (by 34.7-fold), CK-MB (by 8.7-fold), troponin T (by 2.3-fold), myoglobin (by 56.2-fold), were observed. Significant post-race decreases of GFR (by 1.4-fold), triglycerides (by 2.2-fold), were observed. Best pre-race predictors for the risk of AKI were creatinine (inversely), interstitial fluid (positively), extracellular fluid (positively), triglycerides (positively), and blood urea nitrogen (positively).
Chlíbková et al. [64]	*N* = 14, Female = 6, Age male runners 30.0 ± 10.7 yrs, female runners 37.5 ± 12.9 yrs	Prospective	24-h winter ultra-marathon (average − 14.3 °C)	Changes in body composition as well as biomarkers of skeletal and renal damage after a 24-h winter ultra-mountain marathon.	PV, CK, Pcr and PU increased and CrCl decreased. The decrease in BM was negatively related to the increase in CK.
Chlíbková et al. [53]	*N* = 14, Female = 6, Age male runners 30.0 ± 10.7 yrs, female runners 37.5 ± 12.9 yrs	Prospective	24-h winter ultra-marathon (average − 14.3 °C)	Hydration status after a 24-h ultra-marathon under extreme cold weather conditions.	Pre-race and post-race plasma [Na^+] were related to POsmol post-race, but not to fluid intake. Post-race plasma [Na^+], POsmol, urine osmolality and USG remained stable. Post-race Hkt and plasma [K^+] decreased and TTKG increased. Higher pre-race plasma [K^+] was related to higher plasma [K^+] loss post-race.
Mydlík et al. [66]	*N* = 7	Prospective	24-hour run at a stadium	Renal function assessment	Total proteinuria and albuminuria increased significantly after all three types of runs, the least after the 24-hour long-term run. Non-glomerular erythrocyturia was present in the majority of runners after the marathon and 100-kilometre runs and in 2 runners only after the 24-hour run. CK, CK-MB and myoglobin plasma levels increased significantly after all runs. Isoenzyme CK-MB did not exceed 6% of the total catalytic activity. The increases were due to rhabdomyolysis and were associated with myoglobinuria. Urea, creatinine, and phosphorus plasma levels and FEK increased significantly after all three runs, FENa, FECl, FEOSM and FEH_2O decreased. Blood pH was within the reference range during all three runs. Analysis of the base excess and standard bicarbonate after all three runs suggested mild metabolic acidosis.

Table 10 (continued)

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Chalchat et al. [72]	*N* = 11	Prospective field study	24-h run World Championships	Acute response of skeletal/ cardiac muscle and kidney biomarkers	High CK activity (53,239 ± 63,608 U/L) immediately after the race, and remained elevated 24 h after. Circulating myomiR levels (miR-1-3p, miR-133a-3p, miR-133b, miR-208a-3p, miR-208b-3p, and miR-499a-5p) were elevated immediately after the 24-h run (fold changes: 18–124,723) and significantly correlated or tended to significantly correlate with the reduction in CMJ height at 24 h
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	pH increased significantly after 12- and 24-h post-race compared to pre-race levels, whereas pCO_2 decreased significantly in the same span. No significant changes in serum sodium were observed. Serum [K^+] increased significantly immediately after, 12-h, and 24-h after the race by 1.1-fold, 1.2-fold, and 1.5-fold, respectively.

AKI acute kidney injury, *BM* body mass, *CK* creatine kinase, *CK-MB* creatine kinase myocardial band, *CMJ* counter movement jump, *CON* control, *CrCl* creatinine clearance, *CRP* C-reactive protein, *FENa* fractional excretion of sodium, *FECl* fractional excretion of chlorine, *FEOSM* fractional excretion of osmolality, *FEH$_2$O* fractional excretion of water, *GFR* glomerular filtration rate, *Hb* hemoglobin, *Hkt* hematocrit, *hsCRP* high-sensitivity C-reactive protein, *pH* potential of hydrogen, *PCR* plasma creatinine, *POsmol* plasma osmolality, *PU* plasma urea, *PV* plasma volume, *TTKG* transtubular potassium gradient, *USG* urinary specific gravity

Table 11 Effects on the gastrointestinal system

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Lavoué et al. [52]	*N* = 12, Female = 6, Age 46 ± 7 yrs	Prospective	24-h ultra-marathon	Food and fluid consumption during a 24-h ultra-marathon in elite athletes.	Mean fluid intake was 16.4 ± 6.9 L, corresponding to 0.69 ± 0.29 L/h. Mean energy intake was 35.1 ± 15.7 MJ, energy balanced was mainly negative − 29.5 ± 16.1 MJ. 75% of athletes reported symptoms of gastrointestinal distress (nausea being the most frequent one). Race performance was significantly associated with energy intake and negatively with fluid intake.
Gill et al. [65]	*N* = 17, Female = 3, Age 40 ± 7 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on cytokine profile as well as GI system.	After the race, elevated levels of CRP (by 2832%), IL-6 (by 3436%), IL-1β (by 332%), TNF-α (by 35%), IL-10 (by 511%), and IL-8 (by 239%) were observed compared to baseline levels. 75% of finishers reported GI symptoms, with nausea being the most reported symptom (63%). IL-10 and IL-8 were positively associated with gastrointestinal symptoms.
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	AST and ALT were significantly elevated 24-h post-race by 13.5-fold and 3.5-fold.
Wu et al. [36]	*N* = 11, Female = 1, Age 45.1 ± 2.6 yrs	Prospective	24-h ultra-marathon	Changes in hematological, hepatic biomarkers and parameters of iron metabolism in response to a 24-h ultra-marathon.	Total bilirubin, direct bilirubin, ALP, AST, ALT, and LDH increased significantly immediately post-race by 2.2-fold, 2.7-fold, 1.2-fold, 14.4-fold, 3.4-fold, and 3.9-fold, γ-GT did not change significantly. Liver enzymes and cholestasis parameters returned to baseline within 9 days, LDH remained slightly elevated.

ALP alkaline phosphatase, *ALT* alanine aminotransferase, AST aspartate aminotransferase, *CRP* C-reactive protein, *GI* gastrointestinal, *γ-G* γ-glutamyltransferase, *hsCRP* high-sensitivity C-reactive protein, *IL* interleukin, *LDH* lactate dehydrogenase, *MJ* mega joule, *TNF-α* tumor necrosis factor α

74], no incidences of upper respiratory symptoms were found during or following a 24-hour ultra-marathon [56].

Effects on the Hematological System

A 24-hour ultra-marathon also leads to changes in the hematological system [85]. Table 13 summarizes the findings on this topic [33, 35–37, 85]. Such a race leads to a decrease in the number of red blood cells [85], hemoglobin [63, 85], hematocrit [63, 85] and haptoglobin [85]. Regarding the white blood cells, a race of this duration leads to an increase in the total leukocyte count [35], with an increase in neutrophils [24, 35] and monocytes [35]. One study observed notable changes in hematological parameters among participants, including increased liver enzymes and decreased red blood cells counts post-race

Table 12 Effects on the immune system

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Gill et al. [56]	*N* = 36, Female = 17, Age runners 39 ± 7 yrs, control group 32 ± 11 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on salivary anti-microbial protein response and URTIs.	After the race, decreased saliva flow rate (by 36%), salivary IgA (by 33%), and lysozyme (by 41%) secretion rates were observed. An increase in salivary α-amylase secretion rate (by 92%) and cortisol response (by 71%) were observed post-race. Until 4 weeks post-race, no symptoms of URTIs were reported.
Gill et al. [65]	*N* = 17, Female = 3, Age 40 ± 7 yrs	Prospective	24-h ultra-marathon	Effect of a 24-h ultra-marathon on cytokine profile as well as GI system.	Immediately after the race, elevated levels of CRP (by 2832%), IL-6 (by 3436%), IL-1β (by 332%), TNF-α (by 35%), IL-10 (by 511%), and IL-8 (by 239%) were observed compared to baseline. 75% of finishers reported gastrointestinal symptoms, with nausea being the most reported symptom (63%). IL-10 and IL-8 were positively associated with gastrointestinal symptoms.
Hohl et al. [37]	*N* = 25, Age novice runners 43.1 ± 8.7 yrs, experienced runners 41.4 ± 9.1 yrs	Prospective	24-h ultra-marathon	Differences in biomarker changes after a 24-h ultra-marathon between novice and experienced ultra-runners.	In the experienced, a significant time x performance level interaction with a more pronounced increase of cTnT, NT-proBNP, and cortisol. Leukocytes and CRP increased significantly in both groups. Total distance covered correlated significantly with cortisol, CK-MB, cTnT and NT-proBNP.
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	WBC increased significantly immediately after, 12-h, and 24-h after the race by 1.9-fold, 1.8-fold, and 1.9-fold (due to an increase of neutrophils and monocytes). hsCRP was significantly increased 12-h and 24-h post-race by 5.1-fold and 23.1-fold. IL-6 increased significantly immediately after, 12-h and 24-h post-race by 23.3-fold, 31.4-fold, and 32.7-fold.
Waśkiewicz et al. [82]	*N* = 14 Female = 0, mean age 43.0 ± 10.8 yrs, body weight 64.3 ± 7.2 kg, body height 171 ± 5 cm	Prospective field study	24-h ultra-marathon	Changes in oxidative damage and changes in the blood antioxidant defense capacity in endurance-trained athletes	A progressive decline was observed in activities of superoxide dismutase and catalase with the distance covered during the race, while the opposite trend was found in activities of glutathione peroxidase and glutathione reductase that tended to increase. A significant decrease was recorded in glutathione content after completing the marathon distance, which tended toward slightly higher values, without reaching the baseline level, at the finish of the race.

CK-MB creatine kinase myocardial band, *CRR* C-reactive protein, *cTnT* cardiac troponin T, *GI* gastrointestinal system, *Ig* immunoglobulin, *IL* interleukin, *NT-proBNP* N-terminal pro-brain natriuretic peptide, *TNF-α* tumor necrosis factor α, *URTI* upper respiratory tract infection; *WBC* white blood cells

[85]. These findings suggest that ultra-marathon running is linked to a variety of significant changes in hematological parameters, several of which are related to injuries [36].

Motivation and Fatigue

Mental resilience and motivation significantly impact performance. A few studies investigated motivation [86, 87] and the development of both boredom [86] and fatigue [32] during the race (Table 14). Overall, commitment and mental support from a support team seemed to be a significant factor in the success of the best 24-hour ultra-marathon runners [89]. Previous race experience and personal best marathon times are strong predictors of ultra-marathon success. One study indicated that personal marathon best time had the highest impact on 24-hour ultra-marathon race performance [28]. Another study found that physical motivation was negatively associated with mean running speed but positively correlated with the total distance covered, suggesting that intrinsic motivation can influence endurance [87]. Motivation plays a crucial role in the performance and endurance of athletes participating in 24-hour ultra-marathon races. In terms of motivation, there appeared to be no differences between men and women [87]. Older 24-hour ultra-runners were more motivated by the perceived physical benefits of ultra-marathon training and racing. Research showed that older runners are often driven by the perceived advantages of ultra-marathon training and racing. One study revealed that as age increased, so did the focus on health and weight benefits gained through ultra-marathon running [87]. 24-hour ultra-runners who were more

Table 13 Effects on the hematological system

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Liu et al. [85]	*N* = 19, Female = 0, Age 45 (IQR 38–54) yrs	Prospective	2015 Taipei 24 H Ultra-Marathon Festival, Taiwan	Sports anemia and changes in red blood cell viscoelasticity after a 24-h ultra-marathon.	RBC and hemoglobin decreased significantly after the race by 1.01- and 1.04-fold. Haptoglobin decreased significantly by 4.01-fold and ferritin increased significantly by 1.4-fold. Changes in elastic and viscous moduli of erythrocytes correlated significantly with RBC, hemoglobin, and hematocrit.
Waśkiewicz et al. [35]	*N* = 14, Female = 0, Age 43.0 ± 10.8 yrs	Prospective	24-h ultra-marathon	Changes in metabolic parameters after a 24-h ultra-marathon.	WBC increased significantly immediately after, 12-h, and 24-h after the race by 1.9-fold, 1.8-fold, and 1.9-fold (mainly due to an increase of neutrophils and monocytes). hsCRP was significantly increased 12-h and 24-h post-race by 5.1-fold and 23.1-fold. IL-6 increased significantly immediately after, 12-h and 24-h post-race by 23.3-fold, 31.4-fold, and 32.7-fold.
Hohl et al. [37]	*N* = 25 m Age novice runners 43.1 ± 8.7 yrs, experienced runners 41.4 ± 9.1 yrs	Prospective	24-h ultra-marathon	Differences in biomarker changes after a 24-h ultra-marathon between novice and experienced ultra-runners.	WBC and CRP increased significantly in both groups.
Wu et al. [36]	*N* = 11, Female = 1, Age 45.1 ± 2.6 yrs	Prospective	24-h ultra-marathon	Changes in hematological, hepatic biomarkers and parameters of iron metabolism in response to a 24-h ultra-marathon.	No significant changes in RBC, Hb, MCH, and MCV were found directly after the race. RBC and Hb decreased significantly after 2 (by 1.2-fold and 1.2-fold) and 9 days (by 1.1-fold and 1.1-fold) after the race compared to pre-race. Platelets increased significantly directly after the race by 1.1-fold and decreased after 2 days. WBC increased significantly post-race by 2.4-fold, with a predominant increase in granulocytes, lymphocytes decreased significantly immediately after the race by 2.3-fold. Ferritin and transferrin saturation increased significantly directly after the race by 1.8-fold and 1.8-fold and remained elevated after 9 days post-race.
Passaglia et al. [33]	*N* = 20, Female = 0, Age 43.3 ± 9.9 yrs	Prospective	24-h ultra-marathon	Effects of a 24-h ultra-marathon race on clinical, laboratory and echocardiographic data.	Significant increase WBC (by 7.1-fold) were observed, while lymphocytes significantly decreased by 1.3-fold.

hsCRP high sensitive C-reactive protein, *Hb* hemoglobin, *MCH* mean corpuscular hemoglobin, *MCV* mean corpuscular volume, *RBC* red blood cells, *WBC* white blood cells

physically motivated were able to complete more total kilometers [87].

It has been reported that a 24-hour ultra-marathon leads to fatigue in the sense of brain fatigue [32]. In this study of Japanese runners, melatonin and free tryptophan levels changed during the race, while serotonin levels remained constant [32]. The fatigue score increased, the vitality score stayed consistently high, and the scores for anger and hostility were low throughout [study Japa32]. Single starters in a 24-hour ultra-marathon—considered very extreme athletes—showed significantly lower levels of sport-specific trait boredom compared to less extreme athletes, defined as runners competing in a 24-hour relay team. However, boredom can also play a role in single starters [86]. Any ultra-marathon runners intending to compete in a 24-hour race needs to factor boredom into race preparation and performance management during the competition [86]. However, fatigue can also manifest as neuromuscular fatigue. In 24-hour ultra-marathon runners, central factors primarily account for the significant reduction in maximal muscle torque following 24 h of running, particularly in the knee extensor muscles [90]. In a laboratory study during a 24-hour treadmill run, both the running pattern and spring-mass behavior changed over the duration, exhibiting a higher average step frequency, a lower maximum ground reaction force, decreased leg length change during contact, and increased leg and vertical stiffness. Most of these changes were significant from the early phase of the 24 h, specifically during the fourth to sixth hours of running. It was speculated that these factors contributed to an overall limitation of the potentially harmful effects of such a long-duration run on the subjects' musculoskeletal system [91]. Understanding these motivational factors and strategies is essential for athletes aiming to optimize their performance in 24-hour ultra-marathon races.

Table 14 Motivational aspects in 24-hour ultra-marathon running

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Ferrer et al. [87]	*N* = 9, Female = 4, Age 42.14 ± 9.56 yrs	Prospective	24-h ultra-marathon	Psychological motivation for a 24-h ultra-marathon. MOMS	No sex differences in terms of motivation. Perceived physical benefits was main motivational factor for older runners. Markers of physical motivation were positively related to total distance covered but negatively associated with mean running speed.
Gauld et al. [88]	*N* = 12, Female = 1, Age 40.8 ± 8.6 yrs	Multicenter retrospective descriptive study	24-h ultra-marathon	Exercise addiction and personality characteristics in ultra-runners with serious adverse events. EAI. TIPI	Mean of 119.2 km was covered. Mean EAI score was 19.25 ± 4.95 and 91.7% scored above the cut-off considered as symptomatic of exercise addiction, whereas only 8.3% scored "at risk" for exercise addiction. Ultra-runners showed significantly higher scores in emotional stability compared to the general population.
Weich et al. [86]	*N* = 113, Female = 34, Age 37.6 ± 13.8 yrs	Prospective	Competitors of a 24-h ultra-marathon	Boredom, self-regulatory challenges. Before the run, athletes completed self-report measures on sport-specific trait boredom, as well as the degree to which they expected boredom, pain, effort, and willpower to constitute self-regulatory challenges they would have to cope with	Single participating athletes reported a significantly lower sport-specific boredom trait compared to athletes participating as a team. Boredom significantly predicted the occurrence of a crisis during the race with OR 12.5. Analyses revealed that very extreme athletes displayed a significantly lower sport-specific trait boredom than less extreme athletes. With respect to self-regulatory challenges, willpower, pain, and effort were expected and reported at a much higher rate than boredom. However, only boredom was a significant predictor of experiencing a crisis during the competition. Boredom also matters for highly active athletes. The fact that the experience of boredom—and not more prototypical competition-induced challenges, such as pain or effort—was linked to having an action crisis highlights the relevance of incorporating boredom into the preparation for a race and to the performance management during competition.
Ohta et al. [32]	*N* = 15, Female = 3	Field study	24-h ultra-marathon	Measurements of serum levels of serotonin, melatonin, f-Tp, FFA, and levels of BPn. Subjective symptoms were investigated using the Japanese version of the POMS instrument.	Serum melatonin levels at 3 time points were 3.4 ± 0.6 pg/ml, 57.2 ± 15.2pg/ml and 7.8 ± 8.9pg/ml, respectively. Serum f-Trp levels at the 3 time points were 5.4 ± 0.9 nmol/ml, 9.7 ± 2.1 nmol/ml and 11.5 ± 4.9 nmol/ml, respectively. Free fatty acid levels were 0.42 ± 0.10 nmol/ml, 1.26 ± 0.11 nmol/ml and 1.39 ± 0.23 nmol/ml, respectively. Urinary BPn levels increased with time, from 1.2 ± 0.7 nmol/ml to 2.6 ± 1.0 nmol/ml to 4.0 ± 1.5 nmol/ml, respectively. In terms of POMS scores, Factor F increased, but Factor V was high at all time points and showed no marked changes. Scores for anger and hostility were low (Iceberg profile-type: convex type). Urinary BPn levels were correlated significantly with both serum f-Trp level and Factor F. Urinary BPn thus reflected the degree of subjective fatigue with a high level of sensitivity.

BPn biopyrrin, *EAI* Exercise Addiction Inventory, *Factor F* fatigue score, *Factor V* vitality score, *FFA* free fatty acids, *f-Tp* free tryptophan, *TIPI* Ten-Item Personality Inventory, *MOMS* Motivation of Marathoners scale, *POMS* Profile of Mood States

Stress and Recovery

Participating in a 24-hour ultra-marathon places significant physical and psychological stress on athletes, requiring effective recovery strategies to restore optimal function. Recovery after a 24-hour ultra-marathon is multifaceted, involving both physical and psychological components. Several studies have investigated the aspects of stress experienced during the race [24] and recovery after the race [38] (Table 15). A 24-hour race induced perceived stress and led to subsequent alterations in perceived recovery. Stress decreased six days after the race, while recovery returned to pre-race levels 15 days after the race [38]. Efficient recovery after a 24-hour ultra-marathon is essential for restoring physical and mental

Table 15 Aspects of stress and recovery after a 24-hour ultra-marathon

Reference	Sample characteristics	Design	Race characteristics	Variables assessed / Methods	Relevant findings
Nicolas et al. [38]	*N* = 14, Female = 0, Age 43.8 ± 10.2 yrs	Prospective	24-h ultra-marathon	State of stress and recovery following a 24-h ultra-marathon. RESTQ-Sport	Immediately after the race, total stress increased significantly and significantly decreased after 6 post-race days. Total recovery states decreased progressively after the race and significantly after 3 post-race days. Total recovery state values normalized after 15 post-race days.
Ohta et al. [32]	*N* = 15, Female = 3	Field study	24-h ultra-marathon	Measurements of serum levels of serotonin, melatonin, f-Tp and free fatty acid and levels of urinary BPn. Subjective symptoms were investigated using the Japanese version of the POMS	Serum melatonin levels at 3 time points were 3.4 ± 0.6 pg/ml, 57.2 ± 15.2pg/ml and 7.8 ± 8.9pg/ml, respectively. Serum f-Trp levels at the 3 time points were 5.4 ± 0.9 nmol/ml, 9.7 ± 2.1 nmol/ml and 11.5 ± 4.9 nmol/ml, respectively. Free fatty acid levels were 0.42 ± 0.10 nmol/ml, 1.26 ± 0.11 nmol/ml and 1.39 ± 0.23 nmol/ml, respectively. Urinary BPn levels increased with time, from 1.2 ± 0.7 nmol/ml to 2.6 ± 1.0 nmol/ml to 4.0 ± 1.5 nmol/ml, respectively. In terms of POMS scores, fatigue score (Factor F) increased, but vitality score (Factor V) was high at all time points and did not demonstrate any marked changes. Scores for anger and hostility were low (Iceberg profile-type: convex type). Urinary BPn levels were correlated significantly with both serum f-Trp level and Factor F. Urinary BPn thus reflected the degree of subjective fatigue with a high level of sensitivity.
Chalchat et al. [72]	*N* = 11	Prospective field study	24-h run World Championships	Acute response of skeletal/cardiac muscle and kidney biomarkers	High CK activity (53 239 ± 63 608 U/L) immediately after the race, and it remained elevated 24 h after. Circulating myomiR levels (miR-1-3p, miR-133a-3p, miR-133b, miR-208a-3p, miR-208b-3p, and miR-499a-5p) were elevated immediately after the run (fold changes: 18–124,723) and significantly correlated or tended to significantly correlate with the reduction in CMJ height at 24 h
Takayama et al. [24]	*N* = 16, Female = 0		Experimental 24-h run	Investigation of inflammatory responses during and after running and changes in stress responses as determined by serial changes in blood components	A significant increase in hsCRP was seen from 12 h after starting to completion. Ptx3 gradually increased from before starting to after completion, showing a significant difference between pre- and post-run ptx3 levels. WBC count increased significantly up to 6 h after starting. Neutrophils in leukocytosis increased significantly during the first 6 h. Eosinophils decreased significantly over the course of the 24 h. Cortisol increased, and testosterone decreased significantly from 6 h after starting. DHEA-S, myoglobin, and CK increased over the 24 h. d-ROMs changed within the normal range though there was a significant decrease, and BAP stabilized. Active natural killer cells decreased significantly after 24 h running. BPn increased significantly.

BAP biological anti-oxidant potential, *BPn* biopyrrin, *CK* creatine kinase, *CMJ* counter movement jump, *DHEA-S* Dehydroepiandrosterone sulfate, *d-ROMs* Reactive oxygen metabolites, *f-Tp* free tryptophan, *hsCRP* high-sensitivity C-reactive protein, *POMS* Profile of Mood States, *Ptxs3* Pentraxin, *RESTQ-Sport* Recovery Stress Questionnaire for Athletes, *WBC* white blood count

well-being. By implementing the right strategies, athletes can effectively manage stress and encourage comprehensive recovery following a 24-hour ultra-marathon.

The Aspect of Oxidative Stress

Research on oxidative stress during 24-hour ultra-marathons is limited but offers valuable insights into the physiological challenges athletes experience. A few studies have explored oxidative stress during a 24-hour ultra-marathon [32, 82, 92, 93]. In a 24-hour ultra-marathon, paraoxonase 1 (PON1), an antioxidant enzyme, increased after 14 h of running and remained elevated until the end of the race. The same trend was observed for total antioxidant capacity (TAC) values, which correlated positively with PON1 levels. Participants in the 24-hour ultra-marathon exhibited increased levels of pro-inflammatory factors and reactive oxygen species (ROS), leading to oxidative stress. The primary source of ROS was identified as electron leakage from the mitochondrial electron transport chain during adenosine triphosphate (ATP) synthesis [92]. One study reported increased urinary biopyrrin excretion in runners during a 24-hour ultra-marathon. This increase was significantly correlated with serum bilirubin concentrations and the distance covered, suggesting that urinary biopyrrin may serve as a useful marker for oxidative stress in such events [93]. It is assumed that a 24-hour endurance run results in brain fatigue and that oxidative stress may contribute to this [32]. The oxidative metabolite of bilirubin, biopyrrin, is considered a useful candidate marker of oxidative stress in vivo. In 24-hour ultra-marathon runners, urinary biopyrrin excretion was positively and significantly correlated with serum bilirubin concentration and race performance, and could be a useful marker of oxygen stress incurred during a 24-hour ultra-marathon [93]. Further research [94] has highlighted systemic oxidative stress, marked by excessive ROS production, and reduced antioxidative capacity as a consequence of ultra-marathon running. The study emphasized the need for additional research to determine the effects of high training volumes, inadequate recovery periods, and nutritional habits on oxidative stress [94]. These studies have identified significant oxidative stress markers resulting from prolonged endurance exercise. The findings underscore the importance of developing effective strategies to manage oxidative stress for athletes participating in ultra-endurance events.

Skeletal and Locomotor Systems

In 24-hour running races, the skeletal and locomotor systems endure extreme and prolonged demands. These systems are essential for maintaining endurance, stability, and efficiency throughout the event. However, there is very little information regarding the impact of training and competition on the skeletal system. A case report from 1981 about an ultra-marathon runner who broke the world record in the 24-hour run and the trans-America run indicated that the individual was able to run ultra-long distances without sustaining any injuries [95]. A 24-hour ultra-marathon leads to an increase in serum galactosylhydroxylysyl glucosyltransferase (S-GGT) activity and serum type III procollagen aminoterminal propeptide (S-Pro(III)-N-P) concentration [96]. The most likely explanation for the increases in S-GGT and S-Pro(III)-N-P is that prolonged heavy exercise injures the collagen-synthesizing cells of the connective tissue, leading to a short-term increase in type III procollagen production [96]. Continuous running imposes significant stress on bones, joints, and connective tissues, increasing the risk of stress fractures, joint degeneration, and cartilage wear. A narrative review highlighted that acute changes in the locomotor system during ultra-marathons are reversible but can be asymptomatic or painful, emphasizing the importance of monitoring and managing these stresses [97].

Discussion

The present review set out to evaluate the existing literature on 24-hour ultra-marathon running. In the following section, these findings are integrated with evidence from other ultra-endurance race formats to highlight both shared and discipline-specific physiological, psychological, and performance characteristics.

Participation Trends

The results indicated that participation has grown over the years, especially among master runners. This trend is seen globally across various endurance events, including marathons, underscoring a broader demographic shift in long-distance running [98, 99] and other ultra-marathons such as 'Badwater' [100], 'Spartathlon' [101], 'Marathon des Sables' [102, 103] or multi-stage ultra-marathons [104]. Potential explanations for this increase in master ultra-marathoners are better training knowledge and better sports medicine support for older athletes [105], increased popularity of endurance sports as lifelong fitness [106], and ultra-marathons being perceived as more inclusive and less speed-focused than shorter races such as marathons [3].

Performance Trends

All studies indicated that men were faster than women in 24-hour ultra-marathon running, confirming previous findings for other timed ultra-marathon races, such as the 6-hour ultra-marathon [107], the 12-hour ultra-marathon [16] or the 72-hour ultra-marathon [108]. The superior male performance is due to physiological advantages such as higher VO_2max due to larger hearts, higher hemoglobin and greater lung capacity [109]. This allows men to sustain a higher running speed for longer periods. Also, anthropometric advantages do exist where men have more lean muscle mass, especially in the legs [110]. This increases running economy at higher speeds and helps maintain pace in the late race [111]. Although women's higher fat stores can be beneficial for very long events, men's lower body fat improves heat dissipation and reduces energy cost per kilometer [112].

Age of Peak Performance

The average distance achieved in a 24-hour ultra-marathon is ~100 miles, equivalent to a 100-mile ultra-marathon. Regarding the age of peak performance, we found that the best performance in 24-hour ultra-marathon running was achieved between the ages of 40 and 50 years. A study investigating the performance and age of the fastest 100-mile ultra-marathon runners worldwide found that the mean age of the ten fastest runners of the year was 39.2 ± 6.2 years for women and 37.2 ± 6.1 years for men, slightly lower than what we found in 24-hour ultra-marathon running [113]. The age of peak performance in 100-mile ultra-marathon running did not differ between women and men. Furthermore, it showed no changes over the years [113]. A 24-hour race is not just a physical challenge – it is a strategic one. Older athletes tend to excel because they have more years of pacing experience [114], better nutritional and hydration strategies [115], refined psychological resilience [116] and a deeper understanding of how to manage fatigue and discomfort [117]. These skills accumulate over decades, which naturally pushes the peak age upward.

Predictive Variables

Regarding predictor variables, we found that anthropometric characteristics like low body fat percentage, low body mass, or small limb circumferences lacked predictive power when controlled with other factors such as training and prior experience. Overall, prior experience, including personal best marathon time and/or personal best performance in a 24-hour ultra-marathon, proved to be predictive. Similar findings have been reported for other ultra-endurance athletes, such as long-distance inline skaters [118], 100-km ultra-marathon runners [119, 120], multi-stage ultra-marathon runners [121] and IRONMAN® triathletes [122–126]. It can be assumed that ultra-endurance athletes of this level have optimized their training and have already gained a high level of experience in order to successfully compete in a 24-hour ultramarathon [127]. Ultra-endurance performance is far less dependent on classic "runner body" traits than shorter events [110]. When statistically adjusted for training volume, pacing skill, and accumulated experience, characteristics like low body fat percentage, low body mass, and small limb circumferences tend to explain very little additional variance in performance [128]. This is because ultra-events—especially 24-hour races—are dominated by metabolic efficiency, fatigue resistance, pacing discipline, and psychological resilience, none of which are strongly tied to simple body measurements [10]. Prior performance is a holistic proxy for the complex skill set required in ultra-endurance events. This is why experience-based predictors consistently outperform anthropometric ones in statistical models [122, 129].

Pacing

Pacing during a 24-hour ultra-marathon appears to be influenced by sex, age, and performance level, with performance level appearing to be more important than sex or age. A study that assessed sex, age, and performance level in the 'Spartathlon' race also showed that performance rather than age and sex had an impact on pacing [130]. For IRONMAN® triathletes, performance level is also more important for pacing than sex and age [131].

Across multiple analyses of time-limited ultramarathons, the most robust pattern is that elite and subelite runners maintain steadier pacing [132]. They slow down less, recover better from surges, and manage fatigue more effectively [132]. This holds true for men and women, younger and older athletes and different body types [132]. Performance level captures a cluster of traits—experience, training volume, psychological resilience, and pacing skill—that overshadow demographic differences [133]. Women often show a more even pacing, less late-race slowdown and better fatigue resistance [134, 135]. In contrast, men often start faster but slow more [136]. Older runners (especially 40–55 years old) often pace more conservatively and evenly, likely due to greater experience, better self-regulation and more realistic pacing strategies [114]. Performance level integrates multiple underlying factors [134]. This is why it emerges as the strongest predictor. It implicitly includes, training volume and intensity, years of experience, previous race results, psychological endurance, nutritional strategy, and pacing discipline [137].

Exercise-Associated Hyponatremia

An interesting finding was that 24-hour ultra-marathon runners were less likely to develop EAH compared to other running distances and/or other endurance or ultra-endurance sports disciplines [138]. However, a review of EAH in different sports showed that its prevalence was high to very high in ultra-marathon running [138]. For example, a study investigating the prevalence of EAH in the 'Spartathlon' reported that 65% of the investigated finishers developed mild or severe hyponatremia [139]. The low prevalence of EAH in 24-hour ultra-marathon runners may be attributed to the race format, where athletes typically run small laps and are better able to manage their fluid intake. In 24-hour races, average running speeds are substantially lower than in marathons, 50-km, or 100-km events [10]. Lower intensity leads to lower sweat rate, which in turn leads to lower sodium loss and thus to a lower EAH risk [140]. Athletes in shorter or faster events such as marathons often drink more aggressively, sometimes exceeding their fluid needs [141]. In contrast, 24-hour runners typically adopt a more conservative, need-based drinking strategy, which reduces the likelihood of dilutional hyponatremia [23]. Participation in 24-hour events tends to attract runners with more years of endurance experience, better hydration strategies and greater awareness of EAH risks [142]. Experience is a major protective factor, and is more common in this discipline than in shorter ultras [4].

Change in Body Mass

Athletes usually experience a loss of body mass during a 24-hour ultra-marathon, likely due to dehydration as well as a reduction in solid mass, such as skeletal muscle or fat mass. A decrease in body mass is a common occurrence in ultra-marathon running [10] and other ultra-endurance performances such as an IRONMAN® triathlon [142, 143], a multi-stage long-distance triathlon [144], a 100-km ultra-marathon [145] and a multi-stage ultra-marathon [146]. Most likely, ultra-endurance athletes cover their energy deficit by degradation of own-body stores such as body fat [147]. Body mass loss in a 24-hour ultra-marathon is multifactorial, and dehydration is only one piece of the puzzle [10]. Ultra-long events create a unique metabolic environment where several types of tissue and substrate losses occur simultaneously [148]. Even when athletes drink according to thirst, they typically finish with a negative fluid balance [149]. Over 24 h, this can reflect sweat losses, respiratory water loss, and reduced gastrointestinal absorption late in the race [150]. This fluid deficit alone can account for several percentage points of body mass loss [151]. Loss of solid mass also contributes to body mass losses since a 24-hour race is long enough that athletes begin to lose actual tissue mass, not just water [152]. Prolonged running increases muscle protein breakdown [153]. Glycogen depletion leads to associated water loss where each gram of glycogen stores ~ 3 g of water [154]. Micro-damage and catabolism reduce lean mass over the course of the event [155]. Fat mass will be reduced because ultra-endurance intensity relies heavily on fat oxidation and over 24 h, athletes can oxidize hundreds of grams of fat [148]. This contributes to measurable reductions in total body mass [156]. Glycogen stores are progressively depleted during the race. Because glycogen binds water, its loss leads to reduced muscle volume, additional water loss and a further reduction in body mass [157].

Effects on the Cardiovascular System

A 24-hour ultra-marathon impacts the cardiovascular system and results in race-related changes in the ECG and echocardiography [30, 34]. However, these changes fade within a few days post-race [30, 34]. Importantly, the available evidence shows that these race-related changes are short-lived. Within a few days post-race, ECG and echocardiographic measures typically return to baseline [158]. This recovery pattern suggests an effective cardiac adaptation to prolonged endurance stress, no persistent structural abnormalities in healthy, trained athletes and a reversible physiological response rather than pathology [159]. Likewise, elevated biomarkers such as troponin and CK return to their baseline levels within a few days. Yet, such changes are commonly observed in ultra-marathon running [160, 161]. Most importantly, the exercise-induced release of cardiac biomarkers after endurance exercise is not linked to any functional changes or detectable myocardial inflammation or fibrosis [162]. These increases reflect the substantial physiological stress imposed by prolonged endurance exercise and are considered a typical, non-pathological response in trained athletes [163]. Crucially, the available evidence shows that cardiac troponin and CK levels return to baseline within a few days, indicating a transient and reversible response [158]. These biomarker elevations are not associated with functional cardiac impairment, as post-race echocardiography and ECG typically normalize rapidly [164]. Importantly, the exercise-induced release of cardiac biomarkers does not correspond to myocardial inflammation, fibrosis, or structural damage in healthy athletes [165].

Effects on Renal Function

A 24-hour ultra-marathon leads to a transient impairment of renal function. Impaired renal function is a common finding in ultra-marathon running [10] and is most likely due to rhabdomyolysis [166, 167]. Fortunately, elevated markers of renal function, such as elevated serum creatinine, generally return to baseline within 48 h [168]. A 24-hour ultra-marathon places considerable metabolic and mechanical stress on the body, and a temporary reduction in renal function is a well-documented response [10]. This impairment is commonly observed in ultra-marathon runners and is thought to arise primarily from exercise-induced muscle damage and rhabdomyolysis, which increase the renal load through elevated circulating myoglobin, increased creatinine production, and reduced renal perfusion during prolonged exertion [6]. These mechanisms can lead to short-term elevations in markers such as serum creatinine and blood urea nitrogen [169]. Despite these acute changes, the key point is that they are reversible [10]. In healthy, trained athletes, serum creatinine and other renal markers typically return to baseline within 48 h, no persistent renal dysfunction is observed, and the transient impairment reflects physiological stress rather than pathological injury [170]. This pattern mirrors findings across multiple ultra-endurance disciplines, reinforcing that the kidneys are highly adaptable to prolonged exercise stress when hydration, pacing, and environmental conditions are managed appropriately [78].

Effects on the Gastrointestinal System

Gastrointestinal discomfort symptoms often occur during ultra-endurance runs [171]. An increase in markers of gastrointestinal function is often in ultra-marathon runners [10] but is not related to gastrointestinal discomfort [172, 173]. Gastrointestinal discomfort is a common complaint among ultra-endurance athletes, with symptoms such as nausea, bloating, abdominal pain, and diarrhea frequently reported during prolonged exercise [174]. These issues are often attributed to reduced splanchnic blood flow, mechanical stress, and altered gastric emptying during long races [175]. Interestingly, studies show that while biomarkers of gastrointestinal function (e.g., intestinal permeability markers, endotoxin levels) often increase in ultra-marathon runners, these changes are not directly associated with the occurrence or severity of gastrointestinal discomfort symptoms [176]. In other words, subjective symptoms reflect acute functional disturbances (e.g., slowed gastric emptying, mechanical irritation) and objective biomarkers reflect physiological stress on the gut barrier and immune system [177]. The two do not consistently correlate, suggesting different underlying mechanisms [177].

The Effects on the Immune System

A 24-hour ultra-marathon places immense stress on the body's immune system, resulting in an increase in several different markers. However, this reaction is typical in ultra-marathon running [10]. The effect on the immune system in ultra-marathon running seems to depend on the duration of the performance [83]. Although a 24-hour ultra-marathon places immense stress on the body, the changes in immunoglobulin concentrations following an ultra-marathon in experienced ultra-marathon runners suggest an improved immune response that may contribute to the subject's health after the event [178]. Participation in a 24-hour ultra-marathon places immense stress on the immune system, as reflected by increases in several immunological markers immediately after the race [35]. This reaction is typical in ultra-marathon running and represents the body's acute response to prolonged physical exertion [83]. Importantly, the magnitude and nature of the immune response appear to depend on the duration of performance [179]. Longer events, such as 24-hour races, elicit more pronounced changes compared to shorter endurance competitions, highlighting the cumulative impact of sustained exercise stress [180]. Despite the acute stress, evidence suggests that experienced ultra-marathon runners exhibit favorable adaptations where immunoglobulin concentrations often increase following a 24-hour ultra-marathon [10]. Rather than indicating dysfunction, these changes may reflect an enhanced immune readiness. This adaptive response could contribute positively to the athlete's overall health in the days following the event [181]. Thus, while the immune system is challenged during ultra-endurance exercise, the recovery phase may involve beneficial adaptations that strengthen immune competence [178].

Effects on the Hematological System

A 24-hour ultra-marathon leads to changes in blood cells (decrease in red blood cells, increase in white blood cells) which are also common in ultra-marathon running [48, 182]. Generally, the changes in blood cells return to baseline levels after a few days [10]. A fall in red blood cell count or hematocrit after ultra-endurance events is one of the most consistent findings where several mechanisms contribute. Prolonged endurance exercise triggers a rapid increase in plasma volume through fluid intake, sodium retention, and shifts of fluid into the vascular space [183]. This produces hemodilution, lowering measured red blood cell count and hematocrit even when total red cell mass is unchanged [184]. Foot-strike hemolysis, muscle compression, and turbulence in the circulation can destroy a small proportion of erythrocytes. In most athletes this is mild, but over many hours it becomes measurable [185]. Leukocytosis after ultra-endurance races is almost universal and can be dramatic. It is mainly due to stress-hormone–mediated margination where catecholamines and cortisol mobilize neutrophils from the marginal pool into circulation [36]. Furthermore, eccentric loading, tissue breakdown, and gut permeability all stimulate innate immune activation, increasing neutrophils and monocytes [186].

The Aspect of Oxidative Stress

In addition, a 24-hour ultra-marathon leads to oxidative stress. Regarding the effect of oxidative stress on a runner, the training status of the individual seems to be important [187], and the effect seems to vary according to sex and age [188]. Prolonged ultra-endurance exercise reliably increases the production of reactive oxygen and nitrogen species, overwhelming acute antioxidant defenses and leading to measurable oxidative stress [189]. However, the magnitude and physiological consequences of this stress are strongly modulated by individual characteristics such as training, sex and age. Training history is one of the most powerful determinants of oxidative stress responses [190]. Well-trained athletes typically show a lower oxidative damage and a higher antioxidant capacity, both enzymatic (superoxide dismutase, catalase, glutathione peroxidase) and non-enzymatic (glutathione, uric acid) [191]. Chronic endurance training induces mitochondrial adaptations that reduce electron leak, improve redox signaling, and enhance repair pathways [192]. Less-trained individuals experience greater lipid peroxidation, protein oxidation, and DNA damage for the same workload, reflecting a less robust redox buffering system [190]. Sex-related variation is increasingly recognized. Estrogen has intrinsic antioxidant properties, stabilizing membranes and reducing free-radical propagation [193]. Female athletes often show lower markers of oxidative damage at equivalent relative intensities, though this advantage may diminish during very long events when hormonal levels fluctuate or energy availability drops [194]. Male athletes tend to exhibit higher neutrophil activation and ROS production, contributing to greater post-race oxidative load [195]. Age modifies both baseline redox status and the adaptive response to prolonged exertion. Older athletes generally have reduced endogenous antioxidant capacity and greater mitochondrial ROS production, increasing susceptibility to oxidative damage [196]. However, lifelong endurance training can partially offset age-related declines, meaning that training age may be more predictive than chronological age [197]. Younger athletes often show faster post-race recovery of redox balance, reflecting more efficient repair and turnover pathways [198].

Overuse Injuries

Interestingly, we found no studies on the effects on the locomotor system and potential overuse injuries when preparing for a 24-hour ultra-marathon and/or during such a race. Overuse injuries of the lower limbs are very common in runners [11, 199]. Overuse injuries of the lower limbs are among the most common health issues in runners, typically involving structures such as the knee, ankle, Achilles tendon, and plantar fascia [200]. These injuries arise from repetitive mechanical loading, insufficient recovery, and cumulative training stress [201]. While their prevalence is well documented in recreational and competitive runners, specific data on 24-hour ultra-marathon participants remain limited. Given the extreme duration, repetitive strain, and unique pacing strategies of these events, the risk profile may differ substantially from shorter running disciplines [202]. Future studies need to investigate this issue specifically in 24-hour ultra-marathon runners.

Motivation and Fatigue

Motivation is an important aspect of ultra-endurance performance [3, 203]. For the specific population of 24-hour ultra-marathon runners, commitment and mental support from a support team seemed to be a significant factor in the success of the best 24-hour ultra-marathon runners [89]. In terms of motivation, previous experience also appears to be important in achieving the best performance [204]. Motivation is a critical determinant of success in ultra-endurance sports [3]. For athletes competing in 24-hour ultra-marathons, motivation extends beyond individual drive and encompasses external and experiential factors that help sustain performance under extreme physical and psychological stress [204]. Evidence suggests that the presence of a dedicated support crew provides essential mental reinforcement, encouragement, and logistical assistance [205]. This external support appears to be a significant factor in the success of the best ultra-endurance athletes [206]. Prior exposure to ultra-endurance events, including personal best performances, contributes to motivation by fostering confidence, resilience, and realistic pacing strategies [207]. Experienced athletes are better equipped to cope with the psychological demands of prolonged exertion [208]. Endurance athletes often report strong internal drivers such as personal challenge, goal achievement, and self-determination, which sustain effort during periods of fatigue and discomfort [209].

Implications for Future Research

Current evidence reveals no studies investigating post-race nutritional strategies specifically aimed at enhancing recovery after a 24-hour ultra-marathon. Addressing this gap would help clarify how targeted nutritional interventions might accelerate restoration of metabolic, neuromuscular, and immunological function following prolonged continuous exercise. Moreover, the long-term effects of training for and competing in 24-hour events on the locomotor system remain largely unexplored. Future research should examine structural and functional adaptations—or maladaptations—across the skeleton, muscles, tendons, and joints to better understand cumulative loading patterns unique to this race format and their implications for performance, injury risk, and athlete longevity.

Conclusion

Master athletes—typically over 35 years of age—dominate 24-hour ultra-marathon performance. Their extensive experience, optimized training routines, and well-developed nutritional strategies appear to outweigh the physiological advantages of youth, as evidenced by their frequent presence among the top annual performances. A consistent pacing strategy emerges as a defining characteristic of successful athletes. Although pacing varies by sex, age, and performance level, top performers generally maintain the most stable pacing profiles across the full 24 h. Body mass loss is common, with some runners exceeding a 7% reduction even in moderate environmental conditions. This reflects substantial fluid and substrate turnover. Biochemical markers—including CK, AST, and ALT—rise markedly during prolonged running, indicating significant skeletal muscle stress with comparatively minor hepatic involvement. The immune and inflammatory systems respond robustly to the extreme physiological load. Total leukocyte count typically doubles, driven primarily by neutrophilia and monocytosis. Circulating IL-6 can increase nearly 30-fold, and hsCRP more than 20-fold, highlighting the magnitude of systemic inflammatory activation. From a training perspective, high-volume running across varied intensities, supplemented by cross-training, supports both performance and injury mitigation. Ultimately, optimal performance in 24-hour ultra-marathons is multifactorial, requiring the integration of physical conditioning, strategic pacing, nutritional planning, psychological resilience, and accumulated experience. Despite the profound physiological stress imposed by these events, most adverse effects on cardiac, renal, immune, and gastrointestinal systems resolve within several days, underscoring the remarkable adaptability of well-trained ultra-endurance athletes.

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