



Systematic Review

Effects of Precooling on Endurance Exercise Performance in the Heat: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

Laikang Yu ^{1,2,*} , Zhizhou Chen ², Weiliang Wu ², Xinhao Xu ², Yuanyuan Lv ^{1,3}  and Cui Li ^{4,5,*}

¹ Beijing Key Laboratory of Sports Performance and Skill Assessment, Beijing Sport University, Beijing 100084, China; sunflowerly@bsu.edu.cn

² Department of Strength and Conditioning Assessment and Monitoring, Beijing Sport University, Beijing 100084, China; 730415czz@sina.com (Z.C.); wwwuweiliang@163.com (W.W.); x15711324733@163.com (X.X.)

³ China Institute of Sport and Health Science, Beijing Sport University, Beijing 100084, China

⁴ School of Physical Education (Main Campus), Zhengzhou University, Zhengzhou 450001, China

⁵ School of Basic Medical Sciences, Zhengzhou University, Zhengzhou 450001, China

* Correspondence: yulaikang@126.com (L.Y.); lc@zzu.edu.cn (C.L.)

Abstract: An increasing number of studies have explored the effects of precooling on endurance exercise performance in the heat, yet the available results remain inconsistent. Therefore, this study aimed to investigate the effects of different precooling strategies on endurance exercise performance in the heat. A comprehensive search was conducted across PubMed, Web of Science, Cochrane, Scopus, and EBSCO database. The Cochrane risk assessment tool was employed to evaluate the methodological quality of the included studies. A meta-analysis was subsequently conducted to quantify the standardized mean difference (SMD) and 95% confidence interval for the effects of precooling on endurance exercise performance in the heat. Out of the initially identified 6982 search records, 15 studies were deemed eligible for meta-analysis. Our results showed that precooling significantly improved time trial (TT) performance (SMD, -0.37 , $p < 0.01$, $I^2 = 0\%$) and time to exhaustion (TTE) performance in the heat (SMD, 0.73 , $p < 0.01$, $I^2 = 50\%$). Further subgroup analyses revealed that external precooling is more effective in improving TT performance (SMD, -0.43 , $p = 0.004$, $I^2 = 0\%$) and TTE performance (SMD, 1.01 , $p < 0.001$, $I^2 = 48\%$), particularly in running-based performances (TT, SMD, -0.41 , $p = 0.02$, $I^2 = 0\%$; TTE, SMD, 0.85 , $p = 0.0001$, $I^2 = 31\%$). Precooling is an effective approach to improve endurance exercise performance in the heat. External precooling is more effective in improving endurance exercise performance, particularly in running-based performance.

Keywords: precooling; endurance exercise performance; time trial; time to exhaustion



Citation: Yu, L.; Chen, Z.; Wu, W.; Xu, X.; Lv, Y.; Li, C. Effects of Precooling on Endurance Exercise Performance in the Heat: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. *Nutrients* **2024**, *16*, 4217. <https://doi.org/10.3390/nu16234217>

Academic Editor: David C. Nieman

Received: 20 November 2024

Revised: 3 December 2024

Accepted: 5 December 2024

Published: 6 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

A decrease in endurance exercise capacity has been reported when exercising in hot environmental conditions compared to normal and cold environmental conditions [1]. During exercise, high temperature can produce excessive heat stress on the human body, and a series of stress reactions occur, such as increased core temperature, accelerated metabolism, elevated body temperature, and increased sweating with impaired evaporation [2], which is mainly manifested in the advancement of fatigue and a reduction in power output. It has also been pointed out that high temperature can increase the muscle temperature of athletes, leading to a decrease in neuromuscular function and affecting sports performance [3].

Previous studies have shown that the rapid increase in core temperature is the primary factor affecting endurance exercise performance when exercising in the heat [4], and there is a core temperature threshold [5]. When the core temperature rises to reach the core temperature threshold, it will reduce the excitability of the central nervous system and

cardiovascular function, leading to fatigue [6]. Typically, the endurance exercise performance [7] and intermittent exercise performance [8] deteriorate when the core temperature approaches approximately 40 °C, especially in prolonged endurance activities [9].

The current hypothesis suggests that the critical limiting factor for endurance exercise performance in the heat is elevated core temperature [10]. It has been suggested that precooling in the heat decreases the initial core temperature of the athlete and increases the margin between the initial core temperature and the temperature, which affect sports performance, thereby improving endurance exercise performance. The proposal and evaluation of numerous precooling strategies have been prompted by the hypothesized connection between elevated core temperature and diminished endurance exercise performance.

A growing body of research has examined the effects of precooling on endurance exercise performance in the heat, while findings of available studies were conflicting. Previous studies have shown that both internal and external precooling is effective in lowering core temperature, thereby enhancing endurance exercise performance [11,12]. In addition, a meta-analysis indicated that pre-cooling can improve subsequent intermittent and prolonged sports performance in the heat [13]. However, some studies have shown that precooling is effective in lowering body temperature, but is ineffective for endurance exercise performance. For example, Levels et al. [14] and Stevens et al. [15] showed that ice slurry ingestion reduced core temperature but was ineffective for endurance exercise performance. This may be due to the differences in precooling strategies, endurance performance tasks, and types of endurance exercise test.

Two previous meta-analyses have investigated the effects of precooling on endurance exercise performance in the heat. However, one of these meta-analyses also included studies that applied a cooling intervention during exercise [16], which may have influenced their findings regarding the precooling intervention. In addition, the other meta-analysis incorporated studies where the experiments were conducted at temperatures below 26 °C [17], potentially impacting their conclusions about applying precooling interventions in the heat. Therefore, we conducted a comprehensive systematic review and meta-analysis of randomized controlled trials (RCTs) to explore the effects of different precooling strategies on endurance exercise performance in the heat. In this study, we exclusively included studies that applied a cooling intervention prior to exercise and conducted experiments at temperatures above 26 °C [9].

2. Materials and Methods

2.1. Design

This study was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines [18]. The protocol has been registered with PROSPERO (CRD42023448784).

2.2. Search Strategy

We searched the PubMed, Web of Science, Cochrane, Scopus, and EBSCO databases from the inception dates to 6 May 2024, using the following keywords and MESH terms: (1) exercise, exercising, endurance, performance, pace, pacing, sport, sports, sporting, aerobic; (2) precool, pre-cool, pre-cooling, precooling, pre-cooled, precooled, cool, cooled. We also manually searched references listed in the identified systematic reviews and meta-analyses. Two authors independently completed the article screening using a standardized form.

2.3. Eligibility Criteria

Inclusion criteria were (1) RCTs; (2) inclusion of a precooling group and control group; (3) experiments conducted at >26 °C [9]; (4) studies using endurance exercise performance as the outcome measure.

Exclusion criteria were (1) publications that were not in English (such as Korean, Chinese, Japanese, French, German, Russian, Spanish, etc.); (2) studies conducted on animals; (3) reviews articles; and (4) conference papers.

2.4. Data Extraction

Two authors independently performed the data extraction, mainly including (1) study characteristics (first author's surname, publication year); (2) intervention characteristics (precooling strategies, environment conditions, endurance exercise test protocols, types of endurance exercise); (3) subject characteristics (*n*, gender, age); (4) outcome characteristics (endurance exercise performance).

2.5. Methodological Quality Assessment

The methodological quality of the included studies was evaluated using the Cochrane risk of bias tool, which was based on selection bias, performance bias, detection bias, attrition bias, reporting bias, and other biases. Two authors independently conducted the methodological quality assessment, and disagreements were resolved by discussing with a third author. We evaluated the certainty of the cumulative evidence using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) system. Within this framework, the certainty of the evidence was categorized as high, moderate, low, or very low. Our assessment took into account factors such as risk of bias, inconsistency, indirectness, imprecision, and publication bias.

2.6. Statistical Analysis

We extracted the mean and standard deviation (SD) values pertaining to endurance exercise performance in both the precooling and control groups. For studies reporting standard error (SE) and 95% confidence interval (CI), we calculated the SD according to previous studies [19,20]. Data were pooled using fixed- or random-effects models to determine the standardized mean difference (SMD) and 95% CI. The I^2 static was used to assess heterogeneity, where $I^2 < 25\%$, $25 < I^2 < 75\%$, $I^2 > 75\%$ indicate low, moderate, and high heterogeneity, respectively [21,22]. If there was a high heterogeneity ($I^2 > 60\%$), sensitivity analysis and subgroup analysis were used to interpret the results [23].

For subgroup analyses, we tried to investigate the effects of precooling strategies, endurance performance tasks, and types of endurance exercise test on endurance exercise performance in the heat. The forest plots were generated using RevMan 5.4 software (Cochrane, London, UK), and sensitivity analysis and funnel plot were performed using Stata 17.0 software (Stata Corp, College Station, TX, USA). Statistical significance was considered for outcomes with a $p < 0.05$.

3. Results

3.1. Studies Selection

Figure 1 illustrates the initial retrieval of 10,429 records from the databases. A total of 6982 studies remained after excluding duplicates and 74 studies remained after the title and abstract screening. Upon reading the full text, 59 studies were excluded for the following reasons: (1) not related to the theme ($n = 27$); (2) studied irrelevant outcome ($n = 14$); (3) unable to access full text ($n = 9$); (4) no control group ($n = 6$); (5) the experiments were conducted at $\leq 26^\circ\text{C}$ ($n = 3$). Finally, 15 studies [6,24–37] met the inclusion criteria.

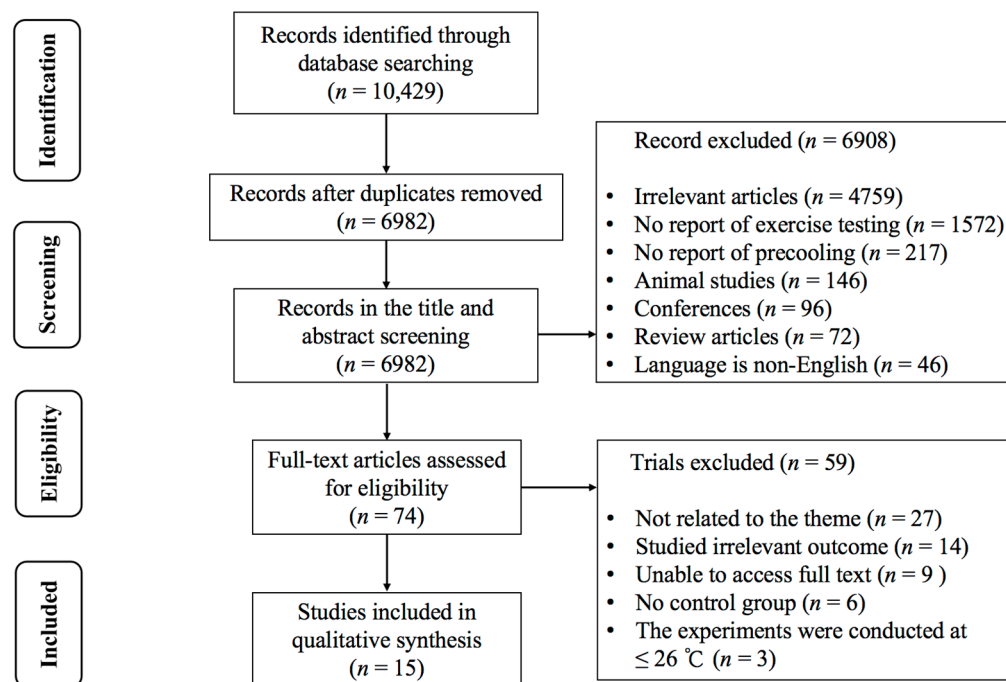


Figure 1. PRISMA flowchart of study selection.

3.2. Characteristics of the Included Studies

Table S1 presents the characteristics of precooling interventions and participants. Among the included studies, there were 236 participants in the 24 precooling groups and 175 participants in the 15 control groups. Of the fifteen studies, ten studies [6,24,25,27,28,30–32,36,37] provided data for time trial (TT) and five studies [26,29,33–35] provided data for time to exhaustion (TTE). In addition, five studies [28, 29,31,34,35] used internal precooling and eleven studies [6,25–27,29,30,32–34,36,37] used external precooling. Furthermore, an endurance exercise performance test was conducted on a treadmill in eight studies [25,26,28–30,33,36,37] and on a bicycle in six studies [6,24,31,32,34,35].

3.3. Meta-Analysis

Our results showed that precooling had a significant effect on improving TT performance [SMD, -0.37 ; 95% CI, -0.60 to -0.14 , $p = 0.002$, $I^2 = 0\%$, Figure 2] and TTE performance [SMD, 0.73 ; 95%CI, 0.41 to 1.05 , $p = 0.00001$, $I^2 = 50\%$, Figure 3].

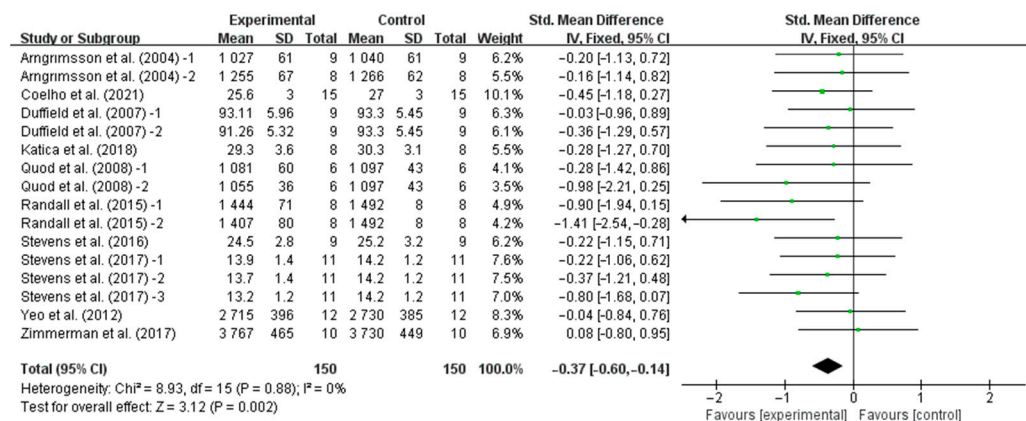


Figure 2. Meta-analysis results of the effects of precooling on TT performance in the heat [6,24,25,27,28,30–32,36,37].

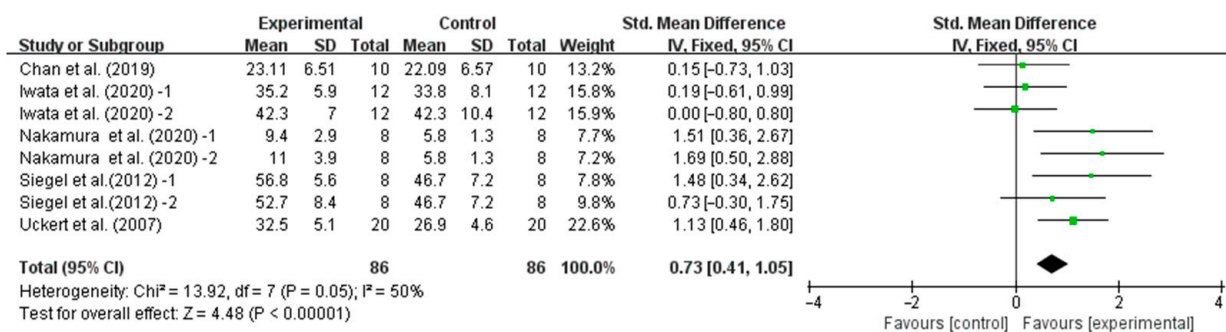


Figure 3. Meta-analysis results of the effect of precooling on TTE performance in the heat [26,29,33–35].

3.4. Subgroup Analysis

3.4.1. TT Performance

Stratifying the analysis by precooling strategies, external precooling significantly improved TT performance (SMD, -0.43 , 95% CI, -0.72 to -0.14 , $p = 0.004$, $I^2 = 0\%$), while internal precooling did not significantly improve TT performance (SMD, 0.01 , 95% CI, -0.58 to 0.61 , $p = 0.96$, $I^2 = 0\%$, Figure 4).

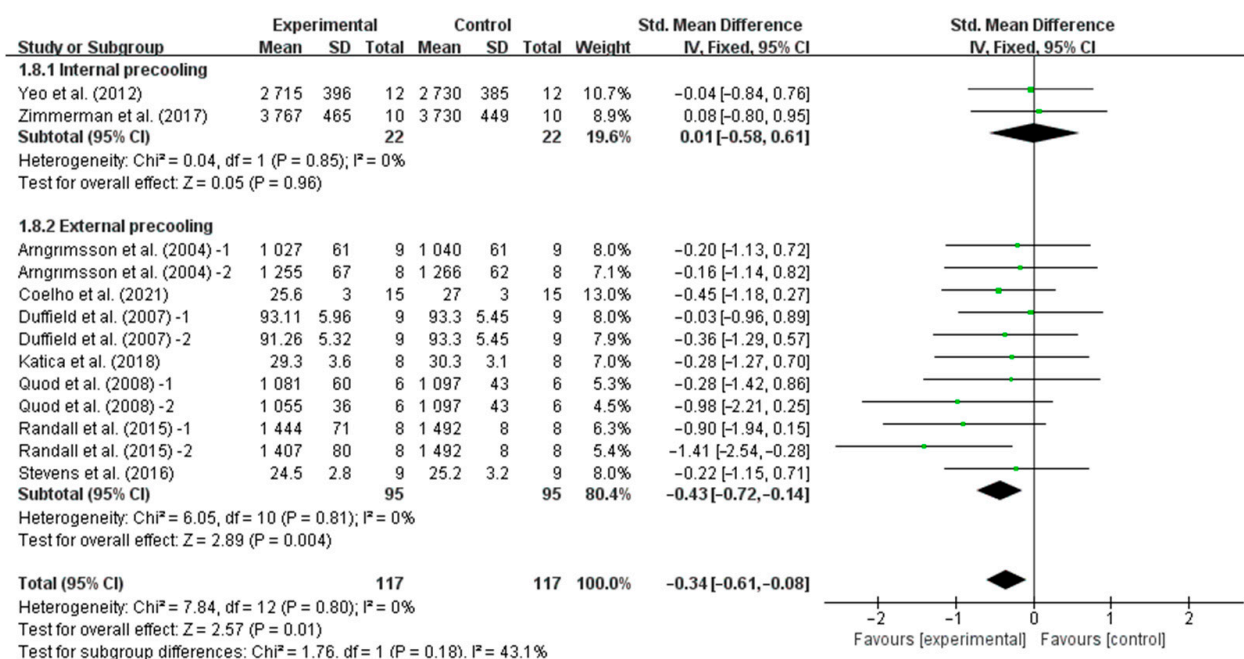


Figure 4. Meta-analysis results of the effects of different precooling strategies on TT performance in the heat [6,25,27,28,30–32,36,37].

In addition, when analyzing the subgroup based on endurance performance tasks, precooling was found to significantly improve TT performance as measured by running (SMD, -0.41 , 95% CI, -0.75 to -0.07 , $p = 0.02$, $I^2 = 0\%$) and cycling (SMD, -0.37 , 95% CI, -0.73 to -0.02 , $p = 0.04$, $I^2 = 0\%$, Figure 5), with running-based TT performance exhibiting a more pronounced effect.

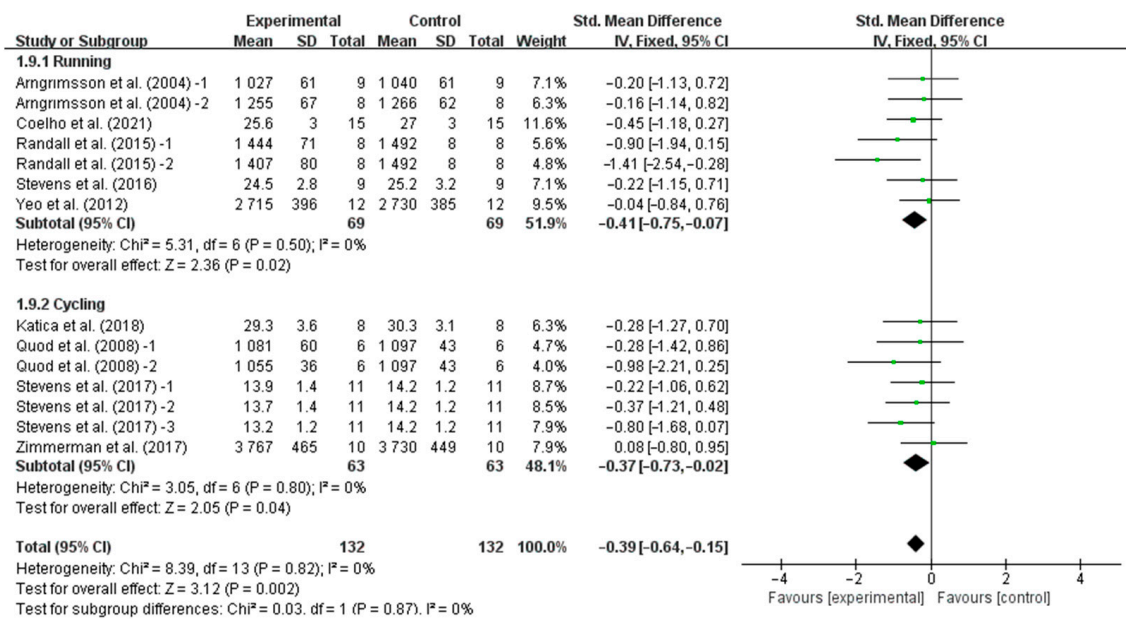


Figure 5. Meta-analysis results of the effects of precooling on running- and cycling-based TT performance in the heat [6,24,25,28,30–32,36,37].

3.4.2. TTE Performance

Stratifying the analysis by precooling strategies, external precooling significantly improved TTE performance (SMD, 1.01, 95% CI, 0.56 to 1.46, $p < 0.0001$, $I^2 = 48\%$), while internal precooling did not significantly improve TTE performance (SMD, 0.44, 95% CI, -0.01 to 0.90, $p = 0.06$, $I^2 = 42\%$, Figure 6).

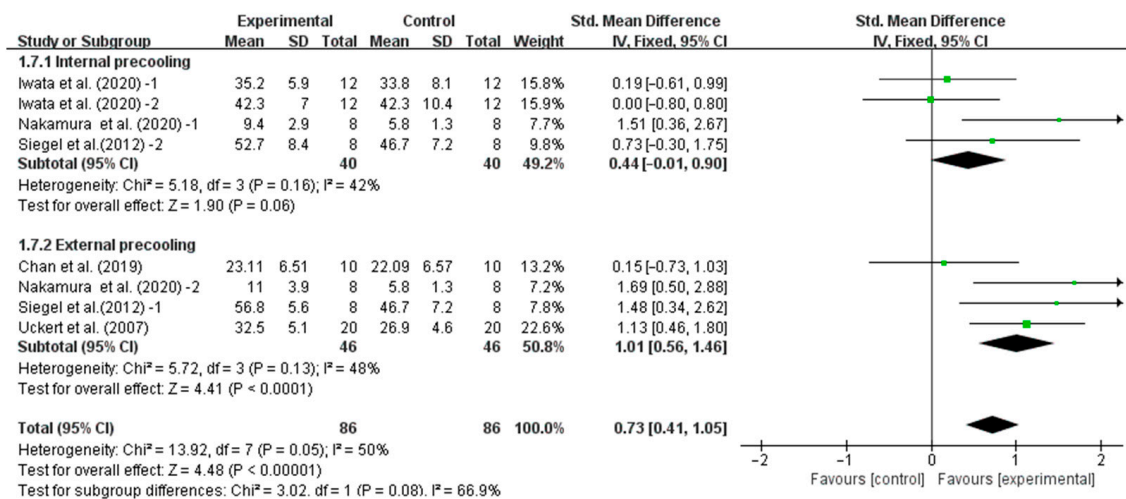


Figure 6. Meta-analysis results of the effect of different precooling strategies on TTE performance in the heat [26,29,33–35].

In addition, when analyzing the subgroup based on endurance performance tasks, precooling was found to significantly improve TTE performance as measured by running (SMD, 0.85, 95% CI, 0.31 to 1.39, $p = 0.002$, $I^2 = 31\%$), while precooling did not significantly improve TTE performance as measured by cycling (SMD, 0.75, 95% CI, -0.08 to 1.58, $p = 0.08$, $I^2 = 66\%$, Figure 7).

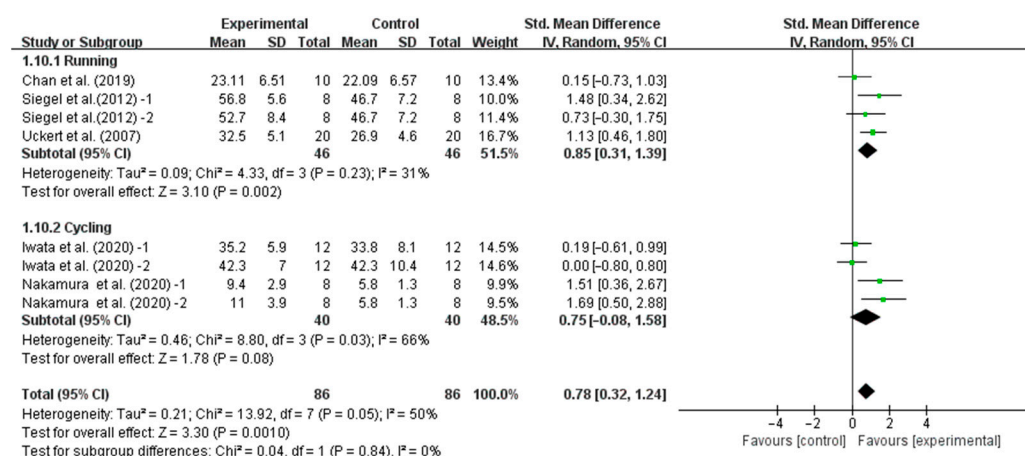


Figure 7. Meta-analysis results of the effect of precooling on running- and cycling-based TTE performance in the heat [26,29,33–35].

3.5. Risk of Bias

We used the Cochrane risk assessment tool to assess the quality of the included studies in terms of biases such as selection, performance, detection, attrition, reporting, and others (Figure S1). The quality was scored according to three levels: low risk, high risk, and unclear. The observed asymmetry in funnel plots indicated the presence of publication bias (Figure S2). As shown in Table S3, we evaluated two evidence syntheses using the GRADE approach. The certainty of the TTE results was rated as moderate, primarily due to potential publication bias, resulting in the downgrading of evidence quality. The TT results were assessed as having low certainty, with the quality downgraded mainly because of a high risk of detection bias, significant statistical heterogeneity, and potential publication bias in the two included studies.

3.6. Sensitivity Analysis

Sensitivity analysis indicated that the positive effects of precooling on TT and TTE performances in the heat remained stable and consistent in both direction and magnitude, regardless of the exclusion of any individual study (Figures S3 and S4).

4. Discussion

The study aimed to explore the effects of different precooling strategies on endurance exercise performance in the heat. A total of 15 studies were included, with the results conclusively demonstrating that precooling had a significant effect on improving TT and TTE performances in the heat. Further subgroup analyses revealed that external precooling is more effective in improving TT and TTE performances, particularly in running-based performances.

4.1. Effects of Precooling on Endurance Exercise Performance in the Heat

This study demonstrated that precooling holds the potential to improve endurance exercise performance in the heat, as indicated by improvements in TT and TTE performance. Our findings align with previous studies, which reported that consuming 1–1.6 L of cold drinks prior to exercise led to an increase in exercise capacity [38]. Athletes who wore an ice singlet for 30 min of precooling before exercise experienced a significantly longer exhaustion time during testing [33]. However, the precise mechanism underlying the beneficial effects of precooling interventions on sports performance in the heat have not been fully elucidated.

Firstly, it is crucial to comprehend the mechanisms by which high-temperature environments induce fatigue impair physical performance. Key factors influencing exercise performance include environmental temperature, relative humidity, an athlete's ability to

regulate core temperature, as well as the intensity and duration of exercise [39]. Studies have highlighted that exposure to high temperature can lead to a decline in neuromuscular function and movement ability [40].

Central fatigue is believed to predominantly affect the function of the central nervous center within the central nervous system. Research into the impact of high temperatures on the central nervous system mainly focuses on cognitive function, sensory response, and neural activation. Within the nervous system, elevated muscle temperature can regulate contractile properties, oxidative capacity, and nutrient substrate utilization. Notably, alterations in muscle temperature directly affect muscle contraction via the nervous system, thus affecting sports performance [41]. For every 1 °C change in muscle temperature, muscle contraction performance changes by 2 to 5% [42]. Compared to moderate temperature, athletes in high-temperature environments experience a faster decline in muscle capacity as exercise intensity increases [43]. A meta-analysis has shown that precooling is a common method employed by athletes to reduce perceived stress in high-temperature environments [15]. In addition, studies on ice slurry intake have reported that consuming ice slurry during rest periods before exercise slows the rise in thermal sensation (TS) during subsequent TTE tests [44]. Furthermore, several studies have demonstrated that ingesting menthol or ice plasma can positively influence the rating of perceived exertion (RPE) and TS, delay the rapid decline in cognitive function and perceptual response, improve the stability of the central nervous system, and contribute to endurance exercise performance in high-temperature environments [45,46]. With the implementation of external precooling strategies, such as applying menthol or low-temperature clothing to the skin surface, positive effects on RPE, TS, and endurance exercise performance have been observed [17,47].

Secondly, the hypothalamus serves as a crucial temperature sensor in the human body, controlling the sending of inhibitory signals during exercise and regulating the selection of exercise intensity [48]. High-temperature environments can influence the hypothalamus to issue premature inhibitory signals, which can be mitigated through precooling before significant brain and muscle dysfunction occurs, thereby reducing central fatigue [49]. Previous studies have shown that precooling strategies can effectively improve athletes' RPE and thermal comfort (TC) during exercise, helping athletes relax their central nervous system, slow down the rate of inhibitory signal transmission from the brain center, and enhance endurance exercise performance [32]. Additionally, Xue et al. [50] found that although precooling measures did not significantly alter sweat rate or body temperature, they had a positive impact on athletes' TC, and the results indicated improved endurance exercise performance. Furthermore, research has demonstrated that TC is fully reduced early in endurance exercise following precooling, and the exhaustion time of the precooling group was significantly longer than that of the non-precooling group in TTE tests. The authors speculated that the precooling strategy fully reduces the stress on the central nervous system, reducing functional consumption and improving endurance exercise performance [34]. Moreover, research has also shown that precooling alters the sensory feedback of the thermoregulatory system, mitigating the overheating protection mechanism of the central nervous system [51], allowing athletes to perform at a higher level for longer periods in high-temperature environments. Increasingly, studies are demonstrating that precooling can reduce the impact of high temperature on the central nervous system and improve athletes' heat storage capacity, effectively improving exercise endurance performance [52].

Body temperature comprises core temperature and peripheral temperature [53]. Core temperature mainly reflects the temperature of vital internal organs within the human body, which can be measured through various internal bodily locations [54]. The peripheral temperature is predominantly composed of skin temperature, subcutaneous tissue temperature, and skeletal muscle temperature [55]. Additionally, variations in both core and skin temperatures are primarily influenced by the external environment's temperature and humidity [56,57]. Research has shown that an elevation in core temperature is the primary factor affecting exercise ability in high-temperature environments [58]. Further-

more, studies have also discovered a critical threshold for core temperature during exercise in the heat [3]. When the core temperature reaches 40 °C, the muscular power output diminishes as the central nervous system initiates adjustments to prevent further rises in core temperature and the corresponding decline in muscle power output [59]. As core temperature rises, neural regions of the brain responsible for movement are inhibited [60], exacerbating fatigue or early termination of exercise due to skeletal muscle exertion and sensory feedback from the cardiovascular system [61]. Moreover, alternation in core temperature and skin temperature can significantly impact an athlete's perception ability [62]. Flouris et al. [63] found that when core temperature rapidly increases due to exercise in a high-temperature environment, athletes' blood pressure and heart rate surge, while their cycling power output decreases.

By using precooling strategies to reduce core temperature before exercise, athletes can increase their body's heat storage capacity [64,65], enabling them to perform more work before reaching a critical core temperature, thereby delaying fatigue and improving endurance exercise performance [63]. The primary effect of the precooling strategy is, therefore, to reduce and stabilize the rise in core and skin temperatures in high-temperature environments [66]. Several studies have shown that without warm-up, the use of precooling strategies can effectively lower core temperature and improve sports performance [67]. Tyler et al. [15] also noted that facial precooling can reduce brain temperature and delay the rise in core temperature, mitigating the negative impact of high temperature on athletes and improving endurance exercise performance. In addition, precooling moderates the increase in core or skin temperature during the warm-up phase, mediated by its effect on RPE [68]. For instance, Riera et al. [69] found that body temperature decreased, RPE diminished towards the latter stages of exercise following precooling, and improved endurance exercise performance was observed at the end. Concurrently, several studies have indicated that the precooling strategy effectively reduces core temperature and aids in maintaining athletes' cognitive ability during exercise [32], while a gradual rise in core temperature during exercise is beneficial for athletes to sustain exercise intensity [70].

Furthermore, athletes must attend to the heat balance of their bodies when exercising in high-temperature environments. Only when the heat production and heat dissipation are in balance can optimal sports performance be achieved [71]. When high ambient temperatures are similar to skin temperature, the heat from the peripheral temperature of the human body must be dissipated through sweating to maintain heat balance [72]. However, during exercise, the human endocrine system may struggle to keep up with the body's heat dissipation demands [73], leading to continuous heat accumulation inside the human body and rapid increase in core and skin temperatures [73]. Watkins et al. [74] reported that precooling reduces heat storage before exercise, improves athletes' heat storage capacity, delays fatigue onset, and enhances endurance exercise performance. Moreover, Ross et al. [75] pointed out that the precooling strategy effectively manages athletes' temperature gradients during exercise, minimizing internal heat loss and maximizing their endurance ability.

During exercise, the central vascular system must fulfill the dual requirements of body temperature regulation and metabolism. When exercising in a high-temperature environment, the heart rate surges rapidly, potentially reaching physiological thresholds or causing exhaustion [76]. Simultaneously, this heightened heart rate shortens the cardiac cycle, resulting in a decrease in cardiac filling, end-diastolic volume, and stroke volume, which in turn reduces cardiac output, mean arterial pressure, and blood flow to skeletal muscle [77,78]. Additionally, as core body temperature rises, reduced circulating blood flow diminishes cardiac filling pressure, while the accelerated heart rate curtails the filling period, leading to a decrease in cerebral blood volume [77], significantly impacting endurance exercise performance. Numerous studies have reported that precooling strategies can mitigate muscle tension stemming from peripheral vascular contraction caused by elevated skin temperature [79], with a primary indicator being increased venous blood flow within the cardiovascular system [80]. Following precooling in a high-temperature environment, the heart rate diminishes, and stroke volume augments during the initial

exercise phase, indicating that precooling enhances blood supply during exercise and bolsters endurance exercise performance [81]. Choo et al. [82] suggested that the heightened stroke volume might stem from augmented venous return due to diminished skin blood flow and improved myocardial contractility resulting from core temperature and sympathetic activation.

Furthermore, Siegel et al. [83] emphasized that precooling strategies can mitigate the heat stress response while concurrently reducing heart rate. Post-precooling and cooling, the exercise-induced heart rate diminishes, stroke volume intensifies, and central blood supply is effectively bolstered.

4.2. Subgroup Analysis

Our subgroup analysis revealed that precooling is more effective in improving running-based TT and TTE performances in the heat. For instance, Stanley et al. [84] reported that men cycling after adopting an internal precooling strategy involving ice slurry intake prior to a 30 min ride showed no improvement in endurance exercise performance. In contrast, Ross et al. [75] found that cold water immersion, an external precooling strategy, reduced skin temperature by 4.4 °C in cyclists and led to a 6% increase in subsequent endurance exercise performance. Additionally, Siegel et al. [29] compared the effects of internal and external precooling and concluded that external precooling was more conducive to endurance exercise performance. This suggests that the precooling strategy is a crucial factor. Previous studies showed that external precooling may more effectively regulate body temperature, control metabolism and heat dissipation, thereby enhancing cognitive function and self-regulation ability in high-temperature environments, leading to improved endurance exercise performance [26,36,37].

The successful implementation of an external precooling strategy to improve endurance exercise performance is attributed to its ability to effectively balance the body's heat conduction, heat convection, and nutrient metabolism [85]. In addition, external precooling mainly acts on the body surface temperature during temperature control, thus preventing excessive heat from evaporating into the environment in hot conditions [86].

The external precooling strategies included in this meta-analysis were head precooling, cold water immersion, and ice clothing. Studies on cold water immersion have found that this method can effectively reduce skin temperature, core temperature, and average body temperature prior to exercise [87], thereby controlling athletes' heat balance and increasing their running distance during endurance exercises lasting over 30 min [88]. Its function is mainly manifested in the soaking of the skin surface in cold water, as a significantly reduced skin temperature enhances athletes' heat storage capacity [89], delays the increase in core temperature, and reduces sweat secretion during exercise. Importantly, the effect of the cold water immersion strategy is consistent with the cooling requirements for endurance exercise in a high-temperature environment [90]. In practice, a cold water immersion program lasting up to 30 min may be more effective than the traditional 60 min program [91]. All studies included in this meta-analysis that utilized the cold water immersion strategy were conducted for less than 30 min.

The practical benefit of ice clothing lies in its ability to allow athletes to pre-cool during warm-up or while at rest [92]. Ice clothing is typically worn for 15–65 min, which is the optimal time frame for effectively reducing skin temperature [93]. In addition, during warm-ups, whole-body blood flow increases, and the cooling effect of the ice suit aids in distributing cooler blood regions across the body surface [15]. Simultaneously, studies have shown that the mean skin and core temperatures in the intervention group were lower than those in the no-precooling group, suggesting that the vest effectively absorbs excess heat generated during warm-ups [94]. When implementing ice clothing, some studies have found that this strategy can also achieve significant results even when athletes have not warmed up [79]. Uckert et al. [26] reported that ice clothing can directly cool unwarmed muscle tissue, lowering skin temperature until core temperature decreases, thereby enhancing the body's heat storage capacity or reducing the perception of thermal

strain in high-temperature environments. Additionally, cooling inactive muscle tissue can lead to local vasoconstriction [95], altering blood flow redistribution and improving blood delivery to hyperthermic muscle tissue [80]. Marsh et al. [95] also confirmed that ice clothing can effectively reduce heart rate after use in the unwarmed phase.

The head precooling strategy aims to reduce temperature in the head, controlling common carotid artery and vein flow and minimizing excessive heat loss gradient changes [16]. Minett et al. [14] showed that head precooling lowers head temperature prior to exercise, mitigating the impact of a high-temperature environment on athletes' cognitive function and enhancing endurance exercise performance. In addition, Harris et al. [78] found that perceived changes in thermal comfort are crucial factors in assessing endurance exercise performance in high-temperature environments. However, several studies have shown that head precooling can benefit the stability of the central nervous system in hot environments [36], while thermal comfort during controlled exercise is negatively affected by the hot environment [96].

A previous study has shown that treadmill tests yield superior results compared to cycling in endurance exercise performance assessments, suggesting that equipment type is a crucial factor [97]. Based on this, meta-analysis studies were divided into treadmill and cycling subgroups. Our subgroup analysis revealed that external precooling is more effective in improving TT and TTE performances on treadmills, indicating their superiority for endurance testing [98,99]. Muscle engagement during running exceeds cycling, and treadmills enable superior performance due to full skeletal muscle engagement and self-regulation during exhaustion [100]. Additionally, VO_2max values are higher on treadmills compared to bicycles under self-paced VO_2 max tests (SPV), with treadmill exercise yielding more stable physiological and psychological indices [101,102].

Numerous studies in this meta-analysis utilized the SPV method, verifying its reliability in assessing aerobic capacity and resembling competitive performances [103]. Treadmill running engages more muscles and provides exercise substrates more efficiently than cycling, with higher VO_2 max values [104,105]. Treadmill exercise also stabilizes central system indicators and cognitive function during exercise [106,107]. Recent research highlights the importance of sacral region stability in endurance testing, which treadmills enhance due to their constant speed and environmental constraints [108,109]. Furthermore, treadmills promote aerobic capacity and energy metabolism development and mitigate bone impact during running [110–112]. Interestingly, in studies conducted by Katica et al. [32], Chan et al. [33], and Stevens et al. [37], researchers applied fan cooling during endurance exercise performance tests involving bicycles. Consequently, compared to cycling, running may diminish convective air cooling, thereby resulting in a more pronounced effect from precooling. Therefore, treadmills may generally outperform bicycles in endurance exercise performance tests among the general population, while for skilled cyclists, bicycles may outperform treadmills.

4.3. Limitations

Several potential limitations of this meta-analysis ought to be acknowledged. Firstly, all the included studies were RCTs of precooling interventions, which inherently precluded complete blinding. Therefore, subjective factors may have influenced the article quality evaluation to some degree. Secondly, the studies included in this meta-analysis solely utilized time as a metric for endurance exercise performance, necessitating caution when extrapolating our findings to related studies focusing on endurance exercise performance. Furthermore, a significant proportion of the included studies involved male subjects, and consequently, this study did not conduct subgroup analysis based on gender. However, the impact of precooling on endurance exercise performance in the heat may be influenced by gender factors. Therefore, future research should further analyze the effects of precooling on endurance exercise performance in different genders, as well as any potential gender differences that may arise. Moreover, the precooling protocols used in the included studies are diverse, so this study only categorizes the precooling strategies into

internal and external precooling for analysis. Therefore, this study is currently unable to provide the most effective specific precooling protocol. Finally, the included studies did not undertake subgroup analyses based on factors such as VO_2max , blood lactate concentration, or pulmonary ventilation. Therefore, future studies may delve deeper into these aforementioned shortcomings.

4.4. Practical Implications

The findings of this study offer several practical implications for athletes, coaches, and sports experts involved in endurance sports and training in the heat. Firstly, athletes can gain an advantage by adding precooling strategies to their pre-event preparations when taking part in endurance events in hot conditions. Since external precooling is quite effective, athletes may consider using ice vests, ice jackets, or cold water immersion as part of their warm-up or pre-competition routines. Secondly, coaches and trainers can include precooling in their training plans to help athletes adjust to hot environments and boost their performance in such conditions, especially for running-based endurance events. Lastly, more research is required to understand the long-term impact of precooling on athlete health and performance, and to find the best precooling protocols for different endurance events and environmental conditions.

5. Conclusions

Precooling is an effective approach to improve endurance exercise performance in the heat. External precooling is more effective in improving endurance exercise performance, particularly in running-based performance.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/nu16234217/s1>, Figure S1: Results of Cochrane risk of bias tool; Figure S2: Funnel plots; Figure S3: Sensitivity analysis results of TT; Figure S4: Sensitivity analysis results of TTE; Table S1: Search strategies; Table S2: Characteristics of studies included in this meta-analysis; Table S3: Strength of outcome evidence.

Author Contributions: Conceptualization, L.Y. and Z.C.; methodology, L.Y., Z.C. and C.L.; software, L.Y. and Z.C.; validation, W.W. and X.X.; formal analysis, L.Y. and Z.C.; investigation, L.Y., Z.C., W.W., X.X., Y.L. and C.L.; resources, L.Y.; data curation, W.W. and C.L.; writing—original draft preparation, L.Y. and Z.C.; writing—review and editing, L.Y., Z.C., W.W., X.X., Y.L. and C.L.; visualization, L.Y. and Z.C.; supervision, L.Y.; project administration, L.Y.; funding acquisition, L.Y. and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Humanities and Social Science Fund of Ministry of Education of China, grant number 24YJC890065, and Chinese Universities Scientific Fund, grant numbers 2024JNPD004, 2024YJSY005.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in the article/Supplementary Material.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CI, confidence interval; PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analysis; RCTs, randomized controlled trials; RPE, rating of perceived exertion; SD, standard deviation; SE, standard error; SMD, standardized mean difference; SPV, self-paced VO_2max ; TC, thermal comfort; TS, thermal sensation; TT, time trial; TTE, time to exhaustion.

References

- Peiffer, J.J.; Abbiss, C.R. Influence of environmental temperature on 40 km cycling time-trial performance. *Int. J. Sports Physiol. Perform.* **2011**, *6*, 208–220. [\[CrossRef\]](#)
- Racinais, S.; Moussay, S.; Nichols, D.; Travers, G.; Belfekih, T.; Schumacher, Y.O.; Periard, J.D. Core temperature up to 41.5 °C during the UCI Road Cycling World Championships in the heat. *Br. J. Sports Med.* **2019**, *53*, 426–429. [\[CrossRef\]](#)
- Nybo, L.; Rasmussen, P.; Sawka, M.N. Performance in the heat—physiological factors of importance for hyperthermia-induced fatigue. *Compr. Physiol.* **2014**, *4*, 657–689. [\[PubMed\]](#)
- Choo, H.C.; Nosaka, K.; Peiffer, J.J.; Ihsan, M.; Abbiss, C.R. Ergogenic effects of precooling with cold water immersion and ice ingestion: A meta-analysis. *Eur. J. Sport Sci.* **2018**, *18*, 170–181. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tyler, C.J.; Wild, P.; Sunderland, C. Practical neck cooling and time-trial running performance in a hot environment. *Eur. J. Appl. Physiol.* **2010**, *110*, 1063–1074. [\[CrossRef\]](#) [\[PubMed\]](#)
- Quod, M.J.; Martin, D.T.; Laursen, P.B.; Gardner, A.S.; Halson, S.L.; Marino, F.E.; Tate, M.P.; Mainwaring, D.E.; Gore, C.J.; Hahn, A.G. Practical precooling: Effect on cycling time trial performance in warm conditions. *J. Sports Sci.* **2008**, *26*, 1477–1487. [\[CrossRef\]](#)
- Parkin, J.M.; Carey, M.F.; Zhao, S.; Febbraio, M.A. Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. *J. Appl. Physiol.* (1985) **1999**, *86*, 902–908. [\[CrossRef\]](#)
- Mohr, M.; Nybo, L.; Grantham, J.; Racinais, S. Physiological responses and physical performance during football in the heat. *PLoS ONE* **2012**, *7*, e39202. [\[CrossRef\]](#)
- Parsons, K. *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance*; CRC-Press: Boca Raton, FL, USA, 2002.
- Maughan, R.J. Distance running in hot environments: A thermal challenge to the elite runner. *Scand. J. Med. Sci. Sports* **2010**, *20* (Suppl. S3), 95–102. [\[CrossRef\]](#)
- James, C.A.; Richardson, A.J.; Watt, P.W.; Gibson, O.R.; Maxwell, N.S. Physiological responses to incremental exercise in the heat following internal and external precooling. *Scand. J. Med. Sci. Sports* **2015**, *25* (Suppl. S1), 190–199. [\[CrossRef\]](#)
- Minett, G.M.; Duffield, R.; Marino, F.E.; Portus, M. Volume-dependent response of precooling for intermittent-sprint exercise in the heat. *Med. Sci. Sports Exerc.* **2011**, *43*, 1760–1769. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tyler, C.J.; Sunderland, C.; Cheung, S.S. The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: A meta-analysis. *Br. J. Sports Med.* **2015**, *49*, 7–13. [\[CrossRef\]](#) [\[PubMed\]](#)
- Levels, K.; Teunissen, L.P.; de Haan, A.; de Koning, J.J.; van Os, B.; Daanen, H.A.M. Effect of warm-up and precooling on pacing during a 15-km cycling time trial in the heat. *Int. J. Sports Physiol. Perform.* **2013**, *8*, 307–311. [\[CrossRef\]](#)
- Stevens, C.J.; Thoseby, B.; Sculley, D.V.; Callister, R.; Taylor, L.; Dascombe, B.J. Running performance and thermal sensation in the heat are improved with menthol mouth rinse but not ice slurry ingestion. *Scand. J. Med. Sci. Sports* **2016**, *26*, 1209–1216. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bongers, C.C.; Thijssen, D.H.; Veltmeijer, M.T.; Hopman, M.T.; Eijssvogels, T.M. Precooling and percooling (cooling during exercise) both improve performance in the heat: A meta-analytical review. *Br. J. Sports Med.* **2015**, *49*, 377–384. [\[CrossRef\]](#) [\[PubMed\]](#)
- Wegmann, M.; Faude, O.; Poppendieck, W.; Hecksteden, A.; Fröhlich, M.; Meyer, T. Pre-cooling and sports performance: A meta-analytical review. *Sports Med.* **2012**, *42*, 545–564. [\[CrossRef\]](#)
- Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *PLoS Med.* **2021**, *18*, e1003583. [\[CrossRef\]](#)
- Li, G.; Lv, Y.; Su, Q.; You, Q.; Yu, L. The effect of aerobic exercise on pulse wave velocity in middle-aged and elderly people: A systematic review and meta-analysis of randomized controlled trials. *Front. Cardiovasc. Med.* **2022**, *9*, 960096. [\[CrossRef\]](#)
- You, Q.; Yu, L.; Li, G.; He, H.; Lv, Y. Effects of Different Intensities and Durations of Aerobic Exercise on Vascular Endothelial Function in Middle-Aged and Elderly People: A Meta-analysis. *Front. Physiol.* **2021**, *12*, 803102. [\[CrossRef\]](#)
- Chen, Y.; Su, Q.; Yang, J.; Li, G.; Zhang, S.; Lv, Y.; Yu, L. Effects of rest interval and training intensity on jumping performance: A systematic review and meta-analysis investigating post-activation performance enhancement. *Front. Physiol.* **2023**, *14*, 1202789. [\[CrossRef\]](#)
- Zhen, K.; Zhang, S.; Tao, X.; Li, G.; Lv, Y.; Yu, L. A systematic review and meta-analysis on effects of aerobic exercise in people with Parkinson's disease. *NPJ Park. Dis.* **2022**, *8*, 146. [\[CrossRef\]](#) [\[PubMed\]](#)
- Tao, X.; Chen, Y.; Zhen, K.; Ren, S.; Lv, Y.; Yu, L. Effect of continuous aerobic exercise on endothelial function: A systematic review and meta-analysis of randomized controlled trials. *Front. Physiol.* **2023**, *14*, 1043108. [\[CrossRef\]](#) [\[PubMed\]](#)
- Stevens, C.J.; Bennett, K.J.; Sculley, D.V.; Callister, R.; Taylor, L.; Dascombe, B.J. A Comparison of Mixed-Method Cooling Interventions on Preloaded Running Performance in the Heat. *J. Strength. Cond. Res.* **2017**, *31*, 620–629. [\[CrossRef\]](#) [\[PubMed\]](#)
- Arngrimsson, S.A.; Pettit, D.S.; Stueck, M.G.; Jorgensen, D.K.; Cureton, K.J. Cooling vest worn during active warm-up improves 5-km run performance in the heat. *J. Appl. Physiol.* (1985) **2004**, *96*, 1867–1874. [\[CrossRef\]](#)
- Uckert, S.; Joch, W. Effects of warm-up and precooling on endurance performance in the heat. *Br. J. Sports Med.* **2007**, *41*, 380–384. [\[CrossRef\]](#)
- Duffield, R.; Marino, F.E. Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. *Eur. J. Appl. Physiol.* **2007**, *100*, 727–735. [\[CrossRef\]](#)

28. Yeo, Z.W.; Fan, P.W.; Nio, A.Q.; Byrne, C.; Lee, J.K. Ice slurry on outdoor running performance in heat. *Int. J. Sports Med.* **2012**, *33*, 859–866. [\[CrossRef\]](#)
29. Siegel, R.; Mate, J.; Watson, G.; Nosaka, K.; Laursen, P.B. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. *J. Sports Sci.* **2012**, *30*, 155–165. [\[CrossRef\]](#)
30. Randall, C.A.; Ross, E.Z.; Maxwell, N.S. Effect of Practical Precooling on Neuromuscular Function and 5-km Time-Trial Performance in Hot, Humid Conditions Among Well-Trained Male Runners. *J. Strength. Cond. Res.* **2015**, *29*, 1925–1936. [\[CrossRef\]](#)
31. Zimmermann, M.; Landers, G.J.; Wallman, K.E. Crushed Ice Ingestion Does Not Improve Female Cycling Time Trial Performance in the Heat. *Int. J. Sport Nutr. Exerc. Metab.* **2017**, *27*, 67–75. [\[CrossRef\]](#)
32. Katica, C.P.; Wingo, J.E.; Herron, R.L.; Ryan, G.A.; Bishop, S.H.; Richardson, M. Impact of upper body precooling during warm-up on subsequent time trial paced cycling in the heat. *J. Sci. Med. Sport* **2018**, *21*, 621–625. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Chan, A.; Yang, Y.; Wong, F.; Yam, M.; Wong, D.; Song, W. Reduction of Physiological Strain Under a Hot and Humid Environment by a Hybrid Cooling Vest. *J. Strength. Cond. Res.* **2019**, *33*, 1429–1436. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Nakamura, D.; Muraishi, K.; Hasegawa, H.; Yasumatsu, M.; Takahashi, H. Effect of a cooling strategy combining forearm water immersion and a low dose of ice slurry ingestion on physiological response and subsequent exercise performance in the heat. *J. Therm. Biol.* **2020**, *89*, 102530. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Iwata, R.; Kawamura, T.; Hosokawa, Y.; Chang, L.; Suzuki, K.; Muraoka, I. Differences between sexes in thermoregulatory responses and exercise time during endurance exercise in a hot environment following pre-cooling with ice slurry ingestion. *J. Therm. Biol.* **2020**, *94*, 102746. [\[CrossRef\]](#)
36. Coelho, L.; Ferreira-Junior, J.B.; Williams, T.B.; Maia-Lima, A.; Borba, D.A.; Silva, C.D.; Coelho, D.B.; Barros, C.L.M.; Prado, L.S.; Silami-Garcia, E. Head pre-cooling improves 5-km time-trial performance in male amateur runners in the heat. *Scand. J. Med. Sci. Sports* **2021**, *31*, 1753–1763. [\[CrossRef\]](#)
37. Stevens, C.J.; Kittel, A.; Sculley, D.V.; Callister, R.; Taylor, L.; Dascombe, B.J. Running performance in the heat is improved by similar magnitude with pre-exercise cold-water immersion and mid-exercise facial water spray. *J. Sports Sci.* **2017**, *35*, 798–805. [\[CrossRef\]](#)
38. Naito, T.; Ogaki, T. Pre-cooling with intermittent ice ingestion lowers the core temperature in a hot environment as compared with the ingestion of a single bolus. *J. Therm. Biol.* **2016**, *59*, 13–17. [\[CrossRef\]](#)
39. Adams, E.L.; Vandermark, L.W.; Pryor, J.L.; Pryor, R.R.; VanScoy, R.M.; Denegar, C.R.; Huggins, R.A.; Casa, D.J. Effects of heat acclimation on hand cooling efficacy following exercise in the heat. *J. Sports Sci.* **2017**, *35*, 828–834. [\[CrossRef\]](#)
40. Cuttell, S.A.; Kiri, V.; Tyler, C. A Comparison of 2 Practical Cooling Methods on Cycling Capacity in the Heat. *J. Athl. Train.* **2016**, *51*, 525–532. [\[CrossRef\]](#)
41. Racinais, S.; Cocking, S.; Periard, J.D. Sports and environmental temperature: From warming-up to heating-up. *Temperature* **2017**, *4*, 227–257. [\[CrossRef\]](#)
42. Racinais, S.; Oksa, J. Temperature and neuromuscular function. *Scand. J. Med. Sci. Sports* **2010**, *20* (Suppl. S3), 1–18. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Nielsen, B.; Nybo, L. Cerebral changes during exercise in the heat. *Sports Med.* **2003**, *33*, 1–11. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Onitsuka, S.; Zheng, X.; Hasegawa, H. Ice slurry ingestion reduces both core and facial skin temperatures in a warm environment. *J. Therm. Biol.* **2015**, *51*, 105–109. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Schulze, E.; Daanen, H.A.; Levels, K.; Casadio, J.R.; Plews, D.J.; Kilding, A.E.; Siegel, R.; Laursen, P.B. Effect of thermal state and thermal comfort on cycling performance in the heat. *Int. J. Sports Physiol. Perform.* **2015**, *10*, 655–663. [\[CrossRef\]](#)
46. Teunissen, L.P.; de Haan, A.; de Koning, J.J.; Daanen, H.A. Effects of wind application on thermal perception and self-paced performance. *Eur. J. Appl. Physiol.* **2013**, *113*, 1705–1717. [\[CrossRef\]](#)
47. Brocherie, F.; Millet, G.P. Is the Wet-Bulb Globe Temperature (WBGT) Index Relevant for Exercise in the Heat? *Sports Med.* **2015**, *45*, 1619–1621. [\[CrossRef\]](#)
48. Nybo, L. Hyperthermia and fatigue. *J. Appl. Physiol. (1985)* **2008**, *104*, 871–878. [\[CrossRef\]](#)
49. Gonzalez-Alonso, J.; Teller, C.; Andersen, S.L.; Jensen, F.B.; Hydlig, T.; Nielsen, B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J. Appl. Physiol. (1985)* **1999**, *86*, 1032–1039. [\[CrossRef\]](#)
50. Xue, Y.; Li, L.; Qian, S.; Liu, K.; Zhou, X.J.; Li, B.; Jiang, Q.; Wu, Z.; Du, L.; Sun, G. The effects of head-cooling on brain function during passive hyperthermia: An fMRI study. *Int. J. Hyperth.* **2018**, *34*, 1010–1019. [\[CrossRef\]](#)
51. Castle, P.C.; Macdonald, A.L.; Philp, A.; Webborn, A.; Watt, P.W.; Maxwell, N.S. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. *J. Appl. Physiol. (1985)* **2006**, *100*, 1377–1384. [\[CrossRef\]](#)
52. Douzi, W.; Dugue, B.; Vinches, L.; Al Sayed, C.; Hallé, S.; Bosquet, L.; Dupuy, O. Cooling during exercise enhances performances, but the cooled body areas matter: A systematic review with meta-analyses. *Scand. J. Med. Sci. Sports* **2019**, *29*, 1660–1676. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Werner, J. System properties, feedback control and effector coordination of human temperature regulation. *Eur. J. Appl. Physiol.* **2010**, *109*, 13–25. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Romanovsky, A.A. Thermoregulation: Some concepts have changed. Functional architecture of the thermoregulatory system. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **2007**, *292*, R37–R46. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Lim, C.L.; Byrne, C.; Lee, J.K. Human thermoregulation and measurement of body temperature in exercise and clinical settings. *Ann. Acad. Med. Singap.* **2008**, *37*, 347–353. [\[CrossRef\]](#) [\[PubMed\]](#)

56. Romanovsky, A.A. Skin temperature: Its role in thermoregulation. *Acta Physiol.* **2014**, *210*, 498–507. [[CrossRef](#)]
57. Kanosue, K.; Crawshaw, L.I.; Nagashima, K.; Yoda, T. Concepts to utilize in describing thermoregulation and neurophysiological evidence for how the system works. *Eur. J. Appl. Physiol.* **2010**, *109*, 5–11. [[CrossRef](#)]
58. Nybo, L. Brain temperature and exercise performance. *Exp. Physiol.* **2012**, *97*, 333–339. [[CrossRef](#)]
59. Casa, D.J.; DeMartini, J.K.; Bergeron, M.F.; Csillan, D.; Eichner, E.R.; Lopez, R.M.; Ferrara, M.S.; Miller, K.C.; O'Connor, F.; Sawka, M.N.; et al. National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. *J. Athl. Train.* **2015**, *50*, 986–1000. [[CrossRef](#)]
60. Tyler, C.J.; Reeve, T.; Hodges, G.J.; Cheung, S.S. The Effects of Heat Adaptation on Physiology, Perception and Exercise Performance in the Heat: A Meta-Analysis. *Sports Med.* **2016**, *46*, 1699–1724. [[CrossRef](#)]
61. Taylor, N.A.; Tipton, M.J.; Kenny, G.P. Considerations for the measurement of core, skin and mean body temperatures. *J. Therm. Biol.* **2014**, *46*, 72–101. [[CrossRef](#)]
62. Bleichert, A.; Behling, K.; Scarperi, M.; Scarperi, S. Thermoregulatory behavior of man during rest and exercise. *Pfluge. Arch.* **1973**, *338*, 303–312. [[CrossRef](#)] [[PubMed](#)]
63. Flouris, A.D.; Schlader, Z.J. Human behavioral thermoregulation during exercise in the heat. *Scand. J. Med. Sci. Sports* **2015**, *25* (Suppl. S1), 52–64. [[CrossRef](#)] [[PubMed](#)]
64. Stevens, C.J.; Dascombe, B.; Boyko, A.; Sculley, D.; Callister, R. Ice slurry ingestion during cycling improves Olympic distance triathlon performance in the heat. *J. Sports Sci.* **2013**, *31*, 1271–1279. [[CrossRef](#)] [[PubMed](#)]
65. Stevens, C.J.; Mauger, A.R.; Hassmen, P.; Taylor, L. Endurance Performance is Influenced by Perceptions of Pain and Temperature: Theory, Applications and Safety Considerations. *Sports Med.* **2018**, *48*, 525–537. [[CrossRef](#)]
66. Maia-Lima, A.; Ramos, G.P.; Moraes, M.M.; Pacheco, D.A.S.; de Oliveira, G.G.A.; de Barros, C.L.M.; Prado, L.S.; Garcia, E.S. Effects of Precooling on 30-km Cycling Performance and Pacing in Hot and Temperate Environments. *Int. J. Sports Med.* **2017**, *38*, 48–54. [[CrossRef](#)]
67. Saldaris, J.M.; Landers, G.J.; Lay, B.S. Physical and perceptual cooling: Improving cognitive function, mood disturbance and time to fatigue in the heat. *Scand. J. Med. Sci. Sports* **2020**, *30*, 801–811. [[CrossRef](#)]
68. Gibson, O.R.; James, C.A.; Mee, J.A.; Willmott, A.G.B.; Turner, G.; Hayes, M.; Maxwell, N.S. Heat alleviation strategies for athletic performance: A review and practitioner guidelines. *Temperature* **2020**, *7*, 3–36. [[CrossRef](#)]
69. Riera, F.; Trong, T.T.; Rinaldi, K.; Hue, O. Precooling does not Enhance the Effect on Performance of Midcooling with Ice-Slush/Menthol. *Int. J. Sports Med.* **2016**, *37*, 1025–1031. [[CrossRef](#)]
70. Bandelow, S.; Maughan, R.; Shirreffs, S.; Ozgüven, K.; Kurdak, S.; Ersöz, G.; Binnet, M.; Dvorak, J. The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. *Scand. J. Med. Sci. Sports* **2010**, *20* (Suppl. S3), 148–160. [[CrossRef](#)]
71. Kenny, G.P.; Jay, O. Thermometry, calorimetry, and mean body temperature during heat stress. *Compr. Physiol.* **2013**, *3*, 1689–1719.
72. Ravanelli, N.M.; Jay, O. Electric fan use in heat waves: Turn on or turn off? *Temperature* **2016**, *3*, 358–360. [[CrossRef](#)] [[PubMed](#)]
73. Jay, O.; Brotherhood, J.R. Occupational heat stress in Australian workplaces. *Temperature* **2016**, *3*, 394–411. [[CrossRef](#)] [[PubMed](#)]
74. Watkins, E.R.; Hayes, M.; Watt, P.; Richardson, A.J. Practical pre-cooling methods for occupational heat exposure. *Appl. Ergon.* **2018**, *70*, 26–33. [[CrossRef](#)] [[PubMed](#)]
75. Ross, M.; Abbiss, C.; Laursen, P.; Martin, D.; Burke, L. Precooling methods and their effects on athletic performance: A systematic review and practical applications. *Sports Med.* **2013**, *43*, 207–225. [[CrossRef](#)]
76. Bentley, D.J.; Newell, J.; Bishop, D. Incremental exercise test design and analysis: Implications for performance diagnostics in endurance athletes. *Sports Med.* **2007**, *37*, 575–586. [[CrossRef](#)]
77. Gonzalez-Alonso, J.; Calbet, J.A. Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation* **2003**, *107*, 824–830. [[CrossRef](#)]
78. Harris, B.A.; Andrews, P.J.; Marshall, I.; Robinson, T.M.; Murray, G.D. Forced convective head cooling device reduces human cross-sectional brain temperature measured by magnetic resonance: A non-randomized healthy volunteer pilot study. *Br. J. Anaesth.* **2008**, *100*, 365–372. [[CrossRef](#)]
79. Bogerd, N.; Perret, C.; Bogerd, C.P.; Rossi, R.M.; Daanen, H.A. The effect of pre-cooling intensity on cooling efficiency and exercise performance. *J. Sports Sci.* **2010**, *28*, 771–779. [[CrossRef](#)]
80. Cheung, S.; Robinson, A. The influence of upper-body pre-cooling on repeated sprint performance in moderate ambient temperatures. *J. Sports Sci.* **2004**, *22*, 605–612. [[CrossRef](#)]
81. Mitchell, J.B.; McFarlin, B.K.; Dugas, J.P. The effect of pre-exercise cooling on high intensity running performance in the heat. *Int. J. Sports Med.* **2003**, *24*, 118–124. [[CrossRef](#)]
82. Choo, H.C.; Nosaka, K.; Peiffer, J.J.; Ihsan, M.; Yeo, C.C.; Abbiss, C.R. Peripheral blood flow changes in response to postexercise cold water immersion. *Clin. Physiol. Funct. Imaging* **2018**, *38*, 46–55. [[CrossRef](#)] [[PubMed](#)]
83. Siegel, R.; Mate, J.; Brearley, M.B.; Watson, G.; Nosaka, K.; Laursen, P.B. Ice slurry ingestion increases core temperature capacity and running time in the heat. *Med. Sci. Sports Exerc.* **2010**, *42*, 717–725. [[CrossRef](#)] [[PubMed](#)]
84. Stanley, J.; Leveritt, M.; Peake, J.M. Thermoregulatory responses to ice-slurry beverage ingestion and exercise in the heat. *Eur. J. Appl. Physiol.* **2010**, *110*, 1163–1173. [[CrossRef](#)] [[PubMed](#)]
85. Charkoudian, N. Mechanisms and modifiers of reflex induced cutaneous vasodilation and vasoconstriction in humans. *J. Appl. Physiol.* (1985) **2010**, *109*, 1221–1228. [[CrossRef](#)]

86. Aldous, J.; Christmas, B.; Akubat, I.; Stringer, C.; Abt, G.; Taylor, L. Mixed-methods pre-match cooling improves simulated soccer performance in the heat. *Eur. J. Sport Sci.* **2019**, *19*, 156–165. [[CrossRef](#)]
87. Kay, D.; Taaffe, D.R.; Marino, F.E. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. *J. Sports Sci.* **1999**, *17*, 937–944. [[CrossRef](#)]
88. Booth, J.; Marino, F.; Ward, J.J. Improved running performance in hot humid conditions following whole body precooling. *Med. Sci. Sports Exerc.* **1997**, *29*, 943–949. [[CrossRef](#)]
89. Vaile, J.; O'Hagan, C.; Stefanovic, B.; Walker, M.; Gill, N.; Askew, C.D. Effect of cold water immersion on repeated cycling performance and limb blood flow. *Br. J. Sports Med.* **2011**, *45*, 825–829. [[CrossRef](#)]
90. Peiffer, J.J.; Abbiss, C.R.; Watson, G.; Nosaka, K.; Laursen, P.B. Effect of a 5-min cold-water immersion recovery on exercise performance in the heat. *Br. J. Sports Med.* **2010**, *44*, 461–465. [[CrossRef](#)]
91. Vaile, J.; Halson, S.; Gill, N.; Dawson, B. Effect of cold water immersion on repeat cycling performance and thermoregulation in the heat. *J. Sports Sci.* **2008**, *26*, 431–440. [[CrossRef](#)]
92. Duffield, R.; Green, R.; Castle, P.; Maxwell, N. Precooling can prevent the reduction of self-paced exercise intensity in the heat. *Med. Sci. Sports Exerc.* **2010**, *42*, 577–584. [[CrossRef](#)] [[PubMed](#)]
93. Moss, J.N.; Trangmar, S.J.; Mackenzie, R.; Tyler, C.J. The effects of pre- and per-cooling interventions used in isolation and combination on subsequent 15-minute time-trial cycling performance in the heat. *J. Sci. Med. Sport* **2021**, *24*, 800–805. [[CrossRef](#)] [[PubMed](#)]
94. Ihsan, M.; Landers, G.; Brearley, M.; Peeling, P. Beneficial effects of ice ingestion as a precooling strategy on 40-km cycling time-trial performance. *Int. J. Sports Physiol. Perform.* **2010**, *5*, 140–151. [[CrossRef](#)] [[PubMed](#)]
95. Marsh, D.; Sleivert, G. Effect of precooling on high intensity cycling performance. *Br. J. Sports Med.* **1999**, *33*, 393–397. [[CrossRef](#)]
96. Vargas, N.T.; Chapman, C.L.; Sackett, J.R.; Johnson, B.D.; Gathercole, R.; Schlader, Z.J. Thermal Behavior Differs between Males and Females during Exercise and Recovery. *Med. Sci. Sports Exerc.* **2019**, *51*, 141–152. [[CrossRef](#)]
97. Fairshier, R.D.; Walters, J.; Salness, K.; Fox, M.; Minh, V.D.; Wilson, A.F. A comparison of incremental exercise tests during cycle and treadmill ergometry. *Med. Sci. Sports Exerc.* **1983**, *15*, 549–554. [[CrossRef](#)]
98. McLaren, S.J.; Graham, M.; Spears, I.R.; Weston, M. The Sensitivity of Differential Ratings of Perceived Exertion as Measures of Internal Load. *Int. J. Sports Physiol. Perform.* **2016**, *11*, 404–406. [[CrossRef](#)]
99. Basset, F.A.; Boulay, M.R. Specificity of treadmill and cycle ergometer tests in triathletes, runners and cyclists. *Eur. J. Appl. Physiol.* **2000**, *81*, 214–221. [[CrossRef](#)]
100. Myers, J.; Bellin, D. Ramp exercise protocols for clinical and cardiopulmonary exercise testing. *Sports Med.* **2000**, *30*, 23–29. [[CrossRef](#)]
101. Hanson, N.J.; Sheadler, C.M.; Lee, T.L.; Neuenfeldt, N.C.; Michael, T.J.; Miller, M.G. Modality determines $\text{VO}_{2\text{max}}$ achieved in self-paced exercise tests: Validation with the Bruce protocol. *Eur. J. Appl. Physiol.* **2016**, *116*, 1313–1319. [[CrossRef](#)]
102. Fanchini, M.; Ghielmetti, R.; Coutts, A.J.; Schena, F.; Impellizzeri, F.M. Effect of training-session intensity distribution on session rating of perceived exertion in soccer players. *Int. J. Sports Physiol. Perform.* **2015**, *10*, 426–430. [[CrossRef](#)] [[PubMed](#)]
103. Hogg, J.S.; Hopker, J.G.; Mauger, A.R. The self-paced $\text{VO}_{2\text{max}}$ test to assess maximal oxygen uptake in highly trained runners. *Int. J. Sports Physiol. Perform.* **2015**, *10*, 172–177. [[CrossRef](#)] [[PubMed](#)]
104. Millet, G. Physiological differences between cycling and running. *Rev. Med. Suisse* **2009**, *5*, 1564–1567. [[CrossRef](#)]
105. Millet, G.P.; Dreano, P.; Bentley, D.J. Physiological characteristics of elite short- and long-distance triathletes. *Eur. J. Appl. Physiol.* **2003**, *88*, 427–430. [[CrossRef](#)]
106. McLaren, S.J.; Weston, M.; Smith, A.; Cramb, R.; Portas, M.D. Variability of physical performance and player match loads in professional rugby union. *J. Sci. Med. Sport* **2016**, *19*, 493–497. [[CrossRef](#)]
107. Halson, L. Monitoring training load to understand fatigue in athletes. *Sports Med.* **2014**, *44* (Suppl. S2), S139–S147. [[CrossRef](#)]
108. Fohrmann, D.; Hamacher, D.; Sanchez-Alvarado, A.; Potthast, W.; Mai, P.; Willwacher, S.; Hollander, K. Reliability of Running Stability during Treadmill and Overground Running. *Sensors* **2022**, *23*, 347. [[CrossRef](#)]
109. Fallahtafi, F.; Gonabadi, A.M.; Samson, K.; Yentes, J.M. Margin of Stability May Be Larger and Less Variable during Treadmill Walking Versus Overground. *Biomechanics* **2021**, *1*, 118–130. [[CrossRef](#)]
110. Santuz, A.; Ekizos, A.; Eckardt, N.; Kibele, A.; Arampatzis, A. Challenging human locomotion: Stability and modular organisation in unsteady conditions. *Sci. Rep.* **2018**, *8*, 2740. [[CrossRef](#)]
111. Ekizos, A.; Santuz, A.; Arampatzis, A. Transition from shod to barefoot alters dynamic stability during running. *Gait Posture* **2017**, *56*, 31–36. [[CrossRef](#)]
112. Hollander, K.; Hamacher, D.; Zech, A. Running barefoot leads to lower running stability compared to shod running-results from a randomized controlled study. *Sci. Rep.* **2021**, *11*, 4376. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.