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COMMENT

Next steps in dehydration and endurance exercise performance research: exploring participant-relevant factors

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Dehydration and endurance exercise

Dehydration is widely recognised as a limiting factor in endurance exercise performance. While dehydration > 2% of body mass is frequently cited as the threshold beyond which performance begins to decline (Funnell et al. 2019; Cheuvront and Kenefick 2014), this threshold is individual and context specific. The extent to which a certain degree of dehydration impairs performance depends on multiple factors, including the environmental conditions and type of dehydration (e.g., intracellular, extracellular, pre-exercise, during exercise), but also potentially training status, heat acclimation, and habitual hydration practices. Nonetheless, when dehydration is present, endurance performance is typically impaired due to a cascade of physiological and perceptual consequences, including exacerbated cardiovascular and thermoregulatory strain, increased glycogenolysis, ratings of perceived exertion and thirst, reduced muscle and cerebral bloodflow, and altered mood (James et al. 2019; Cheuvront and Kenefick 2014).

While the ergolytic effects of dehydration on endurance performance are well established, key areas remain underexplored. Among the most intriguing, at least in our view, are the role of biological sex and the potential for adaptation to repeated exposure to dehydration. As this field continues to evolve, it is essential that future research meaningfully addresses these gaps to develop more refined hydration guidelines and training strategies tailored to diverse groups of athletes. In this commentary, we outline priorities and methodological considerations for future research aimed at advancing the evidence base on the effect of dehydration on endurance performance.

Biological sex and response to dehydration

Research investigating dehydration and endurance performance has largely been conducted in males; consequently, sex-specific comparisons remain unclear even though sex-based physiological differences may play a significant role in how dehydration affects exercise performance (Wickham et al. 2021; James et al. 2019). Females generally have lower absolute and relative total body water, compared to males, largely due to a greater proportion of fat mass and a lower proportion of lean mass (Ritz et al. 2008; Yamada et al. 2022). Therefore, a given percentage of body mass loss represents a greater absolute fluid deficit in females compared to males, potentially amplifying physiological strain and impairing performance.

Daily, weekly, and monthly hormonal fluctuations in females influence sodium regulation, plasma volume, thirst, and resting core temperature, all of which can influence fluid balance (Giersch et al. 2020a, b). Therefore, variations in hormone levels across the menstrual and contraceptive cycles may modulate physiological responses to dehydration depending on the phase (Giersch et al. 2020b).

Females store a smaller percentage of their total body water in the extracellular fluid compartment (Wickham et al. 2021), the source of sweat. As a result, similar sweat losses likely lead to a proportionally greater loss of extracellular

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fluid (i.e., plasma/blood volume) in females, potentially exacerbating the physiological consequences of dehydration. While dehydration increases thermoregulatory strain in both sexes (Cheuvront and Kenefick 2014; Driscoll et al. 2020), this may be more pronounced in females (Giersch et al. 2021; Wickham et al. 2021). Even at mild levels of dehydration, females experience more rapid increases in core temperature and perceived strain (Wickham et al. 2021). Sex differences in sudomotor function may partially explain this disparity, as females typically have lower sweat gland output per gland and a more even sweat distribution across the body (Wickham et al. 2021).

Despite these physiological differences, most research on hydration and exercise performance has either excluded females or not stratified findings by sex, limiting applicability to females. Similar gaps in the literature exist for older adults, where preliminary evidence indicates sex differences in fluid intake patterns during exercise (Baker et al. 2005). With an increasing number of older adults participating in endurance age-category races, the potential importance of an age*sex interaction remains unexplored.

Next steps

Future research should prioritise well-powered sex-comparison studies to clarify whether females are more susceptible to performance decrements from exercise-induced dehydration. Importantly, studies should consider matching fluid deficits to total body water instead of body mass, as relative body mass losses can disproportionately represent fluid deficits in females due to the aforementioned differences in body composition (Ritz et al. 2008). Studies should aim to match males and females by fitness level and heat acclimation status, as well as testing across menstrual and contraceptive cycle phases. In addition, careful consideration should be given to exercise prescription, fixed rates of heat production (e.g., watts per kilogram of body mass or watts per square meter of body surface area) may be preferrable to relative percentage of VO_2max, to reduce bias when comparing sexes (Cramer and Jay 2014).

If sex-differences emerge, further research should explore a range of dehydration severities, environmental conditions, age categories (including consideration of hormonal transitions such as menopause), and exercise modalities (Fig. 1) in females to better reflect the diversity of athletic settings. Such studies would benefit from multi-site collaborations to generate sufficiently large and diverse datasets capable of investigating the complex interactions between these factors (i.e., sex, training status, dehydration severity, and environmental conditions). While laboratory studies should precede field research, if differences between sexes are observed, evaluating larger real-world investigations that measure, but do not control, factors such as menstrual or contraceptive status can bridge the gap between controlled experimentation and applied practice.

Repeated exposure to dehydration: can athletes adapt?

Real-world observations from competitive endurance events show that some athletes may tolerate, and even perform well under modest levels of dehydration (Beis et al. 2012). For example, in 643 marathon runners at the 2009 Mont Saint-Michel Marathon, a significant inverse relationship was observed between body mass loss and finish time, such that those with the greatest body mass loss finished quickest (Zouhal et al. 2011). Similar patterns were documented at the 2000 and 2001 South African Ironman triathlons (Sharwood et al. 2004). Perhaps more remarkably, Haile Gebrselassie won the 2009 Dubai marathon in 2:05:29 despite a reported 9.8% body mass loss (Beis et al. 2012). These findings are not wholly unexpected given that faster athletes typically exhibit higher sweat rates and have less opportunity to consume fluids. Nonetheless, these real-world observations demonstrate that athletes can still perform at a high level despite fluid deficits exceeding the commonly recommended 2% body mass threshold.

This raises an important question; do athletes adapt, physiologically and/or perceptually, to repeated exposure to dehydration? Many athletes likely train under conditions of dehydration, often unknowingly, due to fluid intake practices that are insufficient to replace sweat losses. Nonetheless, if YES, it is practically and scientifically interesting/important to understand how this may alter responses to dehydration and endurance performance. Repeated exposure to dehydration could offer athletes a strategy to prepare for scenarios where fluid intake opportunities are limited during exercise and dehydration is unavoidable.

To date, only two studies have investigated the effect of repeated exposure to dehydration on endurance performance. Fleming and James (2014) found that five exposures to dehydration of ~2.5% body mass reduced the decrement on running time trial performance when dehydrated, potentially mediated by a reduction in perceived exertion. However, the method of inducing dehydration, 24 h fluid restriction combined with fluid restriction during exercise, was atypical and not representative of real-world practices, potentially exacerbating the ergolytic effect of dehydration. In contrast, Deshayes et al. (2021) found that eight exposures to 2% and 4% exercise-induced dehydration over a 4-week period did not attenuate the decline in endurance performance, suggesting no meaningful adaptation to dehydration occurred. These contrasting findings, along with nuanced methodological aspects of both studies, highlight the need to clarify whether, and under what conditions, athletes may adapt to repeated dehydration.

Next steps

Between-group studies comparing athletes who regularly exercise in a dehydrated state (i.e., with minimal or no fluid intake during prolonged exercise) to those who habitually consume fluids during exercise represent a valuable and time efficient approach to explore this avenue of research. Such study designs can provide insights into whether repeated exposure to exercise-induced dehydration leads to physiological and/or perceptual adaptations and subsequently impacts performance. Arguably, well-controlled parallel-group randomised controlled trials, conducted over longer durations with several exposures to exercise in a dehydrated state, could help definitively determine whether repeated exposure attenuates the negative effects of dehydration on performance. Although difficult and time-intensive to undertake, such studies allow investigation into the time course of physiological and perceptual adaptation, if any. If adaptation were to occur, it seems likely that those most negatively impacted by dehydration may benefit the most from repeated exposure to dehydration, a concept that may reflect the large inter-individual variability observed in both acute- (Funnell et al. 2019, 2023) and repeated-exposure to dehydration studies (Fleming and James 2014; Deshayes et al. 2021); this represents an interesting area for future follow-up.

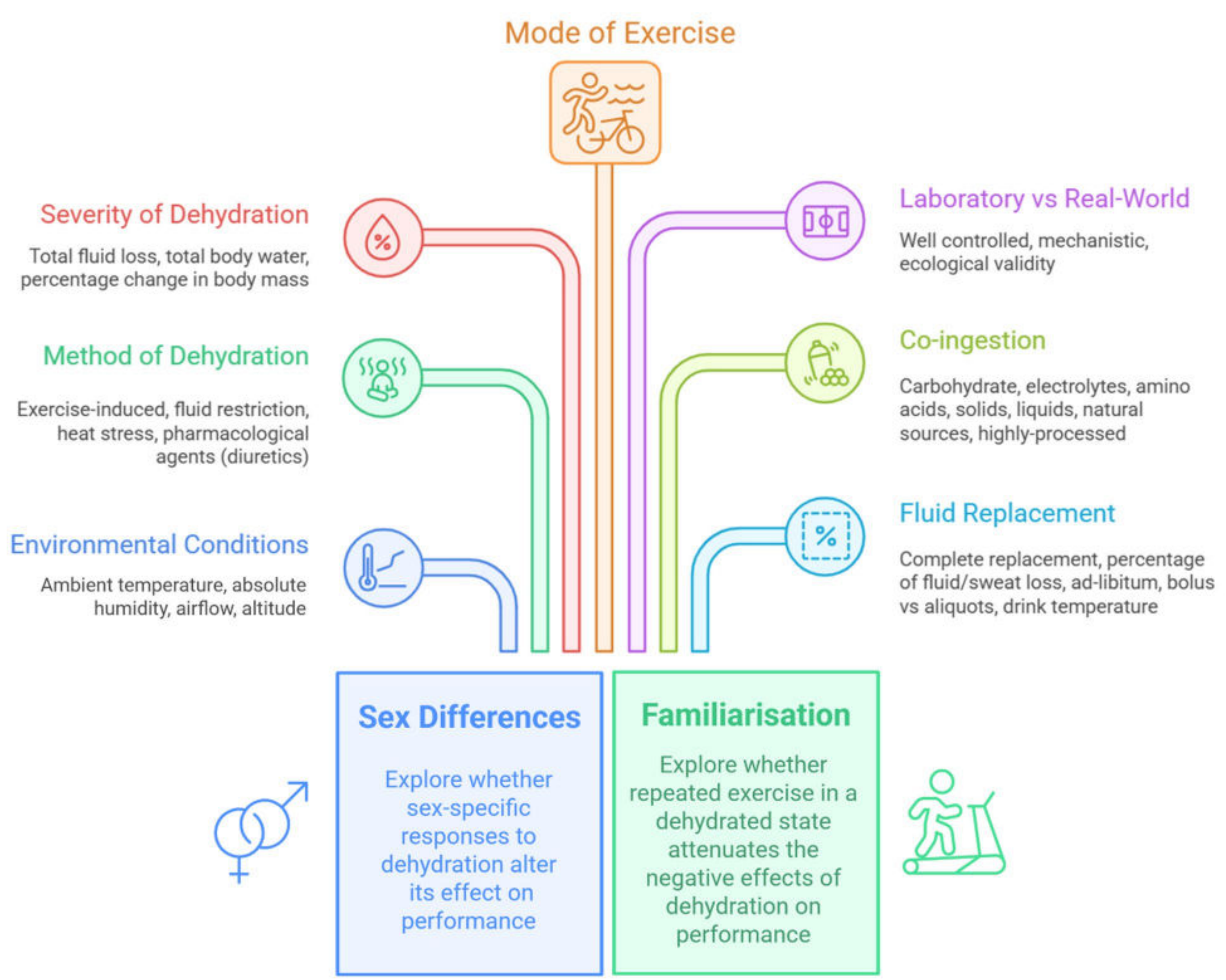

Fig. 1 Overview of two research priorities and methodological considerations for dehydration and endurance exercise performance research. The two research priorities are presented underneath seven key methodological considerations, with exercise mode highlighted as a central consideration when designing future studies

Does exercise mode matter?

Exercise mode is a critical component of study design, yet running remains under-researched in exercise-induced dehydration literature, despite its relevance to real-world athletic scenarios. While some running studies have used exercise-induced dehydration (Funnell et al. 2023; Fallowfield et al. 1996; Casa et al. 2010), others have used pre-exercise fluid restriction (Oliver et al. 2007), diuretics (Armstrong et al. 1985), or a combination of pre-exercise fluid manipulation and exercise (Fleming and James 2014) to induce dehydration. Such methods may over-estimate the negative impact of dehydration on performance due to differing physiological and perceptual effects (James et al. 2019). This distinction is important because runners often train dehydrated from inadequate fluid intake, yet typically begin competition hydrated, making exercise-induced dehydration an ecologically valid model.

Running presents a unique case, as dehydration-induced body mass loss may improve running economy, potentially mitigating some of the performance decrements observed in other exercise modalities. Furthermore, runners typically consume less fluid during exercise (Beis et al. 2012; Armstrong 2021) due to potential gastrointestinal discomfort and limited access to fluids (e.g., difficulty carrying fluids while running, feed stations). As a result, runners may experience exercise-induced dehydration more regularly than athletes in other exercise modalities, and potentially develop a degree of adaptation. Given these factors, endurance runners represent a compelling population for investigating how repeated exposure to exercise-induced dehydration may influence adaptation and performance.

Summary

Whilst evidence demonstrates that dehydration impairs endurance performance, questions remain regarding who is most affected and whether these effects can be mitigated through repeated exposure to dehydration. Biological sex may play a significant role, yet females remain underrepresented in dehydration research, limiting the generalisability of current hydration guidelines. Similarly, the potential for athletes to adapt to repeated exercise in a dehydrated state is poorly understood, despite real-world observations suggesting that high-level performance can occur under significant fluid deficits. Clarifying these uncertainties through well-designed studies represents the logical next steps in hydration and endurance performance research.

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