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"Citius, altius, fortius" in the face of global warming: not as simple as it seems

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In the context of global warming, the reduction in air density, directly driven by rising air temperature, has been identified to enhance athletic anaerobic performance. However, the effect of heat is likely exercise-, intensity- and time-dependent with different physiological mechanisms. It is therefore imperative to clarify some points to not disrupt the disseminated message in order to protect the general population from heat-related illnesses.

Given the increasing concerns regarding the effect of global warming on human activities (*e.g.*, outdoor labor, sports performance) and its subsequent issues on public health, Wang et al.[1] conducted a large-scale qualitative and quantitative analysis with further modeling (*i.e.*, using high and medium greenhouse gas emission scenarios, respectively, over the 1979–2100 period) on the effect of direct (*i.e.*, ambient temperature, dew point, and tailwind speed) and derived meteorological variables (*i.e.*, relative humidity and land surface atmospheric pressure) on the performance of 20 elite athletes in the World Athletics anaerobic disciplines. Results that included several layers of analysis consistently indicated that performances of the athletics anaerobic disciplines (*i.e.*, six sprint [men/women 100 m, 200 m and 400 m distance], four hurdles [women 100 m hurdles, men 110 m hurdles and men/women 400 m hurdles), eight throws [men/women javelin throw, shot put, discus throw and hammer throw] and 8 jumps [men/women long jump, triple jump, pole vault and high jump]) monotonically improve as ambient temperature rises. Additionally, machine learning techniques applied to the 100-m performance data suggested that athletes may achieve faster running times, longer/higher jumps and even greater throwing distances with rising ambient temperatures. We acknowledge the dedication and efforts devoted to this work, which undoubtedly contribute to our understanding of human behavior in the context of global warming. However, we feel compelled to clarify a number of key points in order to convey a clear and unambiguous message on this pivotal topic.

Wang et al.[1] stated that their results *"counter our intuition and is quite distinctive from other human activities and public heath burdens, which were conventionally recognized to be harmed by the increasing temperature at least when temperature is high"*. However, it is essential to note that the positive influence of heat on elite anaerobic athletics performance has previously been demonstrated[2,3]. Research on top ten athletics distance and sprint events (*i.e.*, from 100 m to marathon between 1999 and 2011) performed in either hot (~ 30.0 °C and ~60.0% relative humidity) or thermoneutral (~ 18.5 °C and ~60.0% relative humidity) conditions demonstrated improved sprint (≤ 200 m) performances in the heat (medium to large effect), whereas endurance events (≥ 1500 m) exhibited medium-to-large performance impairments[2]. These activity-related differences in performance under heat stress are supported by physiological mechanisms, with numerous laboratory-based studies demonstrating that muscle heating through passive local or systemic exposure improves single sprint performance[3], certainly linked to a faster early rate of force development observed at the muscle-tendon unit level[4]. Some of the proposed biochemical and contractile mechanisms include (i) a faster rate of phosphocreatine utilization, (ii) a greater activity of glycolytic enzymes (glycogen phosphorylase, phosphofructokinase, and lactate dehydrogenase) and adenine nucleotide degradation, and (iii) an accelerated muscle fiber conduction velocity; all contributing to an increased muscle cross-bridge rate (for details, see Girard et al.[3]). While the benefits of increased muscles temperature are also observed during the first efforts of repeated sprints or high-intensity interval exercise performed under heat stress, subsequent repetitions are altered due to an increase in core and muscle temperatures[5,6]. This clearly illustrates that the effect of heat is likely exercise-, intensity- and time-dependent, with potential clinical issues depending on a myriad of confounding factors *(e.g.*, age, health status, medication). Overall, we argue that it is imperative to not disrupt the disseminated message in order to protect the general population from heat-related illnesses[7,8].

Next, while assuming *"that human physiology and thus the performance-weather relationship keep unchanged during 1979–2100"*[1], one may observe that the increase in air temperature and the resulting decrease in air density, could potentially contribute to enhancing anaerobic performance with global warming. This mechanism being similar to that observed at terrestrial altitude where atmospheric pressure is lower, this raises questions regarding two aspects:

(1) Firstly, the physiological responses to combined heat and altitude/hypoxia appear controversial[9], with some studies reporting antagonistic/blunting effects[10,11], while others propose an additive phenomenon through common protective pathways (i.e., heat shock protein and hypoxia-inducible factors-1α)[12,13]. It is our contention that the global warming-induced alterations in air temperature and/or atmospheric pressure may challenge the dose-response relationship when environmental stress such as heat and altitude are combined, potentially increasing individual physiological strain beyond the impact of reduced air density on anaerobic performance.

(2) Secondly, in elite sport, it is unclear whether the reported improvements in anaerobic athletics performance due to meteorological changes will push the boundaries of maximal physical performance. The historical Olympic motto *"citius, altius, fortius"* (now *"Citius, Altius, Fortius – Communiter"*) has been accompanied by performance progression followed by a plateau in recent decades[14], suggesting a ceiling of many biomechanical, physiological and biological functions in athletes. This opens up debates on understanding human upper limits and translating findings from the sport field into preventive medicine for improved public health[15].

Last, the complementary analysis on the effect of meteorological variables offers intriguing insights. As previously demonstrated[16], Wang et al.[1] assume that ambient temperature is a reliable single variable affecting performance. While including other meteorological variables such as tailwind speed, relative humidity or atmospheric pressure strengthens correlation coefficients, incorporating more complex heat indices such as the Wet-Bulb Globe Temperature (WBGT) and Universal Thermal Climate Index (UTCI) does not provide further insights. This leads to questioning the use of a "one-size-fits-all" approach, such as using a WBGT cut-off value, in reference to human heat-related health and safety[17]. We believe that combining meteorological variables with advanced human heat transfer and thermoregulation models, along with signs and symptoms of heat-related illnesses, could enhance the effectiveness of the "heat-health watch" system[7,8].

To conclude, while the work of Wang et al.[1] provides valuable insights into the effect of meteorological variables and global warming on athletic anaerobic performances, the above-mentioned points collectively underline the critical needs for a multi- and cross-disciplinary approach, including thermal physiology, biometeorology and climate/atmospheric sciences to comprehensively address the significant challenges posed by climate change to human health[8]. Collaboration across these fields is necessary to inform decision-making and enhance heat resilience efforts.

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Author contributions

F.B. drafted the manuscript. O.G. and G.P.M. contributed to the writing of the manuscript. A.M. and J.B. revised the manuscript. All authors approved the final version of manuscript.

Competing interests

The authors declare no competing interests.

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