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To cite this article: Benjamin G. Serpell & Christian J. Cook (2026) Interpreting cortisol and testosterone: are they markers of readiness to perform?, *Stress*, 29:1, 2723347, DOI: [10.1080/10253890.2026.2723347](https://doi.org/10.1080/10253890.2026.2723347)

To link to this article: <https://doi.org/10.1080/10253890.2026.2723347>



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Published online: 31 Aug 2026.



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COMMENT



Interpreting cortisol and testosterone: are they markers of readiness to perform?

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ABSTRACT

Readiness in sport is a topic of interest for many coaches, athletes, and performance support staff alike. In the context of hormones, it has been viewed as a response to stress (i.e. increasing free cortisol and testosterone). However, whether a causal relationship exists for cortisol and testosterone with performance remains unclear. Free cortisol and testosterone possibly remain best viewed as relevant biomarkers of the stress response, with this response also being, in part, a proxy measure of readiness. The priming of cortisol and testosterone through exercise, warm-up, or other stimuli to prepare for performance has been a recurring theme amongst research; however, the results in terms of both the magnitude of hormone change and influence on subsequent performance are highly variable. In fact, cortisol and testosterone change in the context of readiness appears individual in nature and are affected by physiology, training status, age, sex, trained state, and individuals' perceptions of both their liking and the magnitude of the stressor. The importance of individuality in this context is poorly understood, and an opportunity exists to undertake research to increase the understanding and application of strategies that may enhance readiness to perform in females and males.

ARTICLE HISTORY

Received 28 April 2026
Accepted 18 August 2026

KEYWORDS

Stress; testosterone; cortisol; performance; sex; training status

Introduction

Coaches and athletes commonly seek performance-enhancing interventions that offer a competitive advantage while taking into consideration existing workloads. Of increasing interest is readiness. Readiness has been defined in many ways—physiologically, it is commonly referred to as an athlete's performance capacity (i.e. physiological capacity minus fatigue markers) (Morton et al., 1990). From a psychological perspective, readiness has been defined as an athlete's ability to look inward and access resources to “cope” with demands of competition (Jones et al., 2002). However, readiness is clearly multidisciplinary and has been more recently, and perhaps more accurately, defined as a state representing a person's physical recovery, psychological willingness to compete, and capacity to execute tasks both as an individual and as an active team member (Serpell et al., 2018; Taylor et al., 2012). Throughout this manuscript, we assume this final definition to be true. Furthermore, given this definition, it is clear readiness requires, amongst other elements, stress resilience.

Stress can be defined as any occurrence that challenges the mind or body to adapt; it shapes and remolds us constantly in adaptive, and sometimes maladaptive, ways (Serpell & Cook, 2021; Serpell et al., 2018; Serpell et al., 2023). However, the term “stress” is often used interchangeably with terms such as “depression” and “anxiety,” implying stress to be negative. Depression and anxiety are possible outcomes following over-exposure to stress (Serpell & Cook, 2021), and stress is only “negative” when loading is inappropriate and adaptation does not occur. In context, when strength training, the body is placed under physical stress; if the chronic loading is insufficient adaptation does not occur, if the loading is too great injury can occur, appropriate loading results in adaptive growth; similar applies to emotional stress. More

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importantly, in an acute sense, warm-ups in sport, for example, by their very nature, are likely to be stressful (physically and mentally) (Serpell & Cook, 2025); however, a well-designed and executed warm-up is critical for preparing to train or compete (Serpell & Cook, 2026). Thus, a planned and graded intensity stress may be used to enhance readiness (Serpell et al., 2018).

Stress has neuroendocrine/physiological (i.e. hormonal) implications (Crewther et al., 2021). Exposure to stress can stimulate activation of the hypothalamic–pituitary–adrenal (HPA) axis to increase the production of glucocorticoids (e.g. cortisol), and rising cortisol levels can stimulate (or in some cases inhibit) the hypothalamic–pituitary–gonadal (HPG) axis to increase (or decrease) the secretion of sex steroids (e.g. testosterone) (Crewther et al., 2021, 2025). However, individual perceptions of the stressor (e.g. its magnitude and likeability) may influence the magnitude of the cortisol and testosterone response (Serpell et al., 2019), and it should be noted that both cortisol and testosterone have been linked to performance and various human behaviors across a range of contexts.

Previous work has suggested dual effects of cortisol and testosterone on the neuromuscular system and the potential for these hormones to inform practice to enhance performance (Crewther et al., 2011). This is despite hormones research being characterized by considerable methodological variability (Hayes et al., 2016). Recent research has demonstrated that similar hormone change or correlations may be observed to a given stress irrespective of the sampling procedure (Crewther et al., 2025). Nevertheless, despite research amassing in support, whether a causal relationship for cortisol and testosterone with sporting performance exists, or if these hormones are simply biomarkers of stress response and readiness, remains unclear (Bermon & Garnier, 2017; Serpell et al., 2024). Therefore, the aim of this short leading article is to provide an “update” of work in the space of hormones and readiness. Here, we (1) provide a summary on the link for cortisol and testosterone with readiness and performance; (2) give a high-level overview of strategies that may be used to alter the hormonal profile; and (3) discuss the importance of individuality in the hormonal response to stress, including female-to-male differences. We conclude with practical implications.

Cortisol, testosterone, performance, and readiness

Cortisol can be arousing and has been linked to performance in some short-duration sporting events. For instance, high pre-competition cortisol concentration has been shown to map to performance in Judo in males (Papacosta et al., 2016), and similar observations have been made when the cortisol concentration increases from pre-competition to within-competition in Judo in males and in Olympic Weightlifting in males and females (Crewther et al., 2019; Papacosta et al., 2016). Interestingly, however, although evidence is mixed for and against, cortisol has also been linked to rowing performance in some contexts (Maestu et al., 2005)—a “longer” duration sporting event; which is consistent with the energy provision nature of cortisol. Nevertheless, it is important to note that elevations in, or high concentrations of, cortisol can lead to considerable behavioral change, and in prolonged doses may increase fatigue and anxiety (Papacosta et al., 2016; Serpell & Cook, 2021; Serpell et al., 2018). Furthermore, increases in cortisol are catabolic, so there will be an accompanying metabolic cost (Torres et al., 2021).

Testosterone has been linked to enhanced motivation, motor control, neuromuscular expression of speed and power, assertiveness, and collaborative competitiveness (Cook & Beaven, 2013; Cook et al., 2018; Serpell et al., 2018, 2023). The mechanisms by which these functional outcomes can occur include the activation of signaling pathways that promote the mobilization of energy stores, the regulation of neuromotor units, and the accumulation of protein for skeletal muscle hypertrophy via mTor (Cook et al., 2021; Smith et al., 2013). Unsurprisingly, therefore, elevations in free testosterone have been linked to enhanced performance in less combative sports (compared to martial arts/fighting sports), longer duration events, and team sports in both males and females. For instance, in males, pre-event free testosterone concentration has been linked to performance for several track and field key performance indicators (Bezuglov et al., 2023; Crewther et al., 2012), and higher and increasing concentrations of testosterone have been mapped to performance in professional Rugby union (Crewther et al., 2018; Gaviglio et al., 2014) and Surfing (Cook et al., 2024; Serpell & Cook, 2026). In females, the free testosterone concentration, and increases in testosterone, has been linked to performance indicators in Rugby 7's (Mason et al., 2023), Hockey performance (Crewther et al., 2018), and some Track and Field events (Bermon

& Garnier, 2017; Serpell & Cook, 2026). Furthermore, similarly to cortisol, in some contexts testosterone has been linked to Rowing performance (Maestu et al., 2005).

Though, in isolation, cortisol and testosterone have both been linked to performance in a range of contexts, and the two hormones are often considered relative to each other using the testosterone-to-cortisol ratio (Serpell & Cook, 2021; Serpell et al., 2018, 2020, 2023; Strahorn et al., 2017). As such, readiness in sports is often associated with high or increasing levels of both testosterone and cortisol, particularly when testosterone increases are greater in magnitude than cortisol increases (Serpell et al., 2018). Additionally, the testosterone-to-cortisol ratio may also have some flow on effect on recovery, with a high ratio being linked to more rapid and “better” recovery (Lac & Berthon, 2000).

Despite data slowly amassing to suggest some relationship, in the absence of ethically and safety challenging pharmaceutical interventional experiments, causality between hormones and performance remains difficult to propose. Most research which has explored linkages between cortisol and testosterone and sporting performance has measured free testosterone, not total serum cortisol and testosterone; the difference between the two being that free testosterone is unbound from protein and available for use. While free hormones have been shown to have a stronger association with lean mass, muscular strength and power and physical function in some populations (Lolck et al., 2025), it is important to realize that “available” is not synonymous with “used;” but could increase likelihood. Furthermore, in the absence of dose–response knowledge, interpretation also remains difficult. In some studies, while statistically significant results have been obtained, the magnitudes of change in free hormones is less than 10%, which seems unlikely to have any marked physiological effects (D’Andrea et al., 2020). Hence, testosterone and cortisol may remain best viewed as potential biomarkers of performance (or processes that underline performance).

Strategies to alter hormone profile (and potentially enhance readiness)

There are pharmaceutical and other potentially illegal strategies that have been widely employed in sport, which can alter the hormone profile and have been shown to impart performance benefits (e.g. steroid administration); at the detriment to health, and possibly morality (Pope et al., 2014). The doses, often anecdotally reported but on occasion accurately measured, are best described as absurd and clearly supraphysiological (e.g. C J Hunter, a former shot put world champion who failed a drug test leading into the 2000 Sydney Olympics, allegedly tested at 1000× the IOC allowed level (Pfister & Gems, 2015)). Recently, possible benefits from much lower endogenous (i.e. natural) variations in cortisol and testosterone concentrations have also been explored (Cook & Crewther, 2014; Cook et al., 2021; Crewther et al., 2019, 2011; Gaviglio et al., 2014; Papacosta et al., 2016; Serpell et al., 2023).

“Natural” strategies to optimize endogenous hormone profiles have been trialed with some success in potentiation, Weightlifting, and Sprint models (Kelekian et al., 2022; Kilduff et al., 2013). Such strategies can be physical (e.g. short intense bouts of exercise that are not metabolically fatiguing prior to competition (Serpell et al., 2018)) or psychosocial (e.g. motivational presentations, social connectedness/readiness contagiousness (Cook & Crewther, 2014; Serpell et al., 2018)). Research reports that the effectiveness of psychosocial methods is highly variable (Cook et al., 2021), and while physical interventions are also variable, they appear to be linked to baseline hormones, concentration changes, and trained state (Cook et al., 2021; Crewther et al., 2012).

Considerations for cortisol and testosterone similarities and differences within and between females and males

Testosterone has previously been somewhat neglected as relevant in females; however, new work is emerging that suggests that it is important for stress adaptation and athletic performance in women to an extent similar, or perhaps surpassing, males (Cook et al., 2018; Cook, Crewther, et al., 2021; Cook, Fourie, et al., 2021; Crewther et al., 2018). Although, as with other sports science research, where it has been reported that only 30%–40% of all sports science research has included female participants and only 6% of studies have investigated females exclusively (Cowley et al., 2021), it should be recognized that our current understanding of athlete readiness from a hormonal perspective is limited by the majority of work mostly being conducted with males.

The total testosterone concentration differs between females and males, however free testosterone may overlap (Cook et al., 2021). Therefore, female and male acute free cortisol and free testosterone response to stress, and associated functional outcomes, can be similar. Though variation in the hormonal response to stress may be greater for females, particularly when a menstrual cycle overlay is considered (Cook et al., 2021).

For males, the gonads (i.e. male reproductive organs) account for a significant amount of testosterone production. For females, outside of ovulation, peripheral mechanisms make up nearly 50% of testosterone by means of conversion of androstenedione (Cook et al., 2021). Just prior to ovulation, there is typically a large and continuous surge of gonadotropin releasing hormone from the hypothalamus associated with estrogen production, which can activate pituitary release of luteinizing hormone and follicle-stimulating hormone and stimulate additional testosterone production from ovaries as well as contribute to increased peripheral conversion (Cook et al., 2021). As a result, some, but by no means all, females show baseline testosterone peaks soon after estrogen peaks (see Figure 1), with the likelihood of testosterone peaks appearing from limited studies to be greater in trained females (Cook et al., 2018, 2021; Crewther & Cook, 2018). This, in part, could help explain why variation in the free testosterone response to acute stress is typically greater for females than for males. However, for females using certain hormonal contraceptives, testosterone levels appear to “flatten” although the average baseline across a cycle timeline may be slightly higher compared to those not using hormonal contraceptive (Crewther et al., 2018; Vibarel-Rebot et al., 2015).

From a responsiveness perspective, in female team sports, the use of oral contraceptives has been associated with differences in both salivary testosterone and cortisol responses to heavy training and competition scenarios, and free testosterone was further linked to coach-rated positive behavioral actions during competition (Cook et al., 2018; Crewther et al., 2015, 2018). Interestingly, a relatively recent study suggested that females appear more sensitive to dihydrotestosterone (DHT) changes than males are under heavy load training (Cook et al., 2021). DHT comes about from the metabolism of free testosterone; as such, speculatively, DHT is an amplification of free testosterone, which may be related to the efficient use of the free testosterone component and adaptation to heavy training (Cook et al., 2021; Smith et al., 2013).

In summary, when considering male–female differences in the context of testosterone and cortisol, while testosterone and cortisol production differs in mechanisms between males and females, qualitatively, similarities in response have been observed. However, a reoccurring theme with hormones

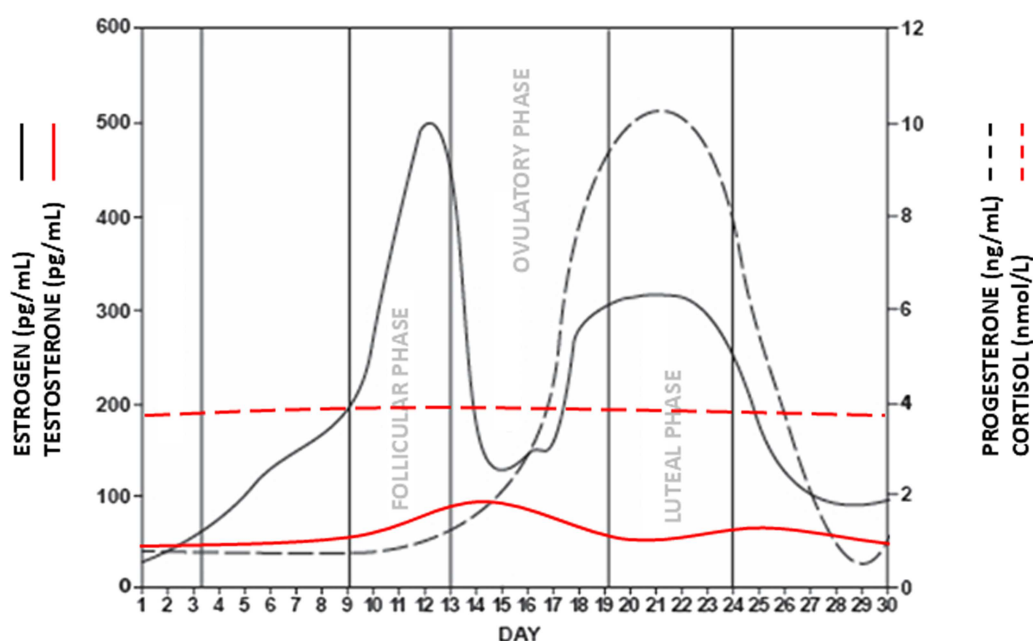


Figure 1. Baseline hormone variation for women with a regular menstrual cycle and obvious testosterone peak, not using a hormonal contraceptive.

appears to be their high degree of response individuality. For example, while some females show clear menstrual patterns in testosterone, others do not. The use of hormonal contraceptives appears to contribute, and, as will be discussed in more depth in the next section, so does the trained state (Cook et al., 2021; Crewther et al., 2015, 2018). Where individual changes are observed across the menstrual cycle changes in behavior and motivation also appear to co-vary (Cook & Beaven, 2013; Cook et al., 2021; Van Goozen et al., 1997). Nevertheless, though the data in females remains too sparse for conclusion an early speculative stage linkage between stimulus induced increases in testosterone, cortisol and behavior in females appears similar to that seen in males, with individuality outweighing any sex differences in responsiveness.

Individuality and cortisol and testosterone change

Variability in response to physical and psychosocial strategies that can be used to optimize endogenous hormone profiles highlights that individuality in males and females is a key feature observed for hormone change for both magnitude of change and the effect itself in terms of training or competitive outcomes (Beaven, Gill, et al., 2008; Beaven, Cook, et al., 2008). This point is highlighted when one considers the outcomes from several recent studies—research with a mixed cohort of trained, untrained, male and female cyclists with varying trained states; and other work with a healthy, but only recreationally active, population of chess players. Researchers have observed a significant exercise stimulus induced spike in testosterone for highly trained cyclists, male or female, in different trained states; but a smaller spike for recreational cyclists (Cook et al., 2021; Smith et al., 2013). Furthermore, in the study with chess players, it was seen that the same exercise protocol used in the cyclist studies had no effect on the participants (Serpell et al., 2025). This observation may explain, in part, the differing hormonal response between both cohorts of cyclists and chess players – physiologically some (i.e. the highly trained cyclists) may have been “responders” and some (i.e. chess players) may be “non-responders” (see Figure 2).

That the physiological/hormonal response to stress may differ between individuals is not surprising. Research has linked high testosterone to high lean muscle mass (Hakkinen et al., 1992; Mouser et al., 2016; Taylor et al., 2022), and individual differences are likely further highlighted when considering recent work in Judo, which showed that the baseline cortisol concentration may be suppressed following acute bouts of high intensity exercise. In the Judo study, it was argued that this was possibly because cortisol secretion may be moderated by high levels of creatine kinase—a biomarker of muscle damage (Crewther et al., 2024); trained systems appear to have more sophistication in levels of “control”. Potentiation, the use of a high intensity stimulus to elicit a further prolonged increase in power also shows a dependence on highly trained features, with stronger, more powerful athletes much more prone to positive outcomes from its use (Crewther et al., 2011).

While individuality is likely to exist with respect to physiological/hormonal response to a given stressor, it remains pertinent to remember that individuality in response to stress may also come about from how one perceives the stressor. In the previous example of chess players vs. cyclists, for example, the chess players may have found the sprint protocol on the cycle ergometer excessively stressful, whereas the trained cyclists may have experienced it simply as an acceptable challenge. In a recent study in competitive surfing, the likeability of a warm-up was one of the key components linked to performance outcome, and interestingly associated with hormonal change (Serpell & Cook, 2025). Alternatively, and speculatively, hormone priming stimuli for chess players may require lesser physical and higher mental intensities.

Given the importance of considering individuality in the hormonal response to stress, it is clear that there is a reasonable argument to examine, alongside group analyses, individual and responder factors (e.g. high, medium or low responders) and the nature of the response to very different stimuli (e.g. mental vs physical intensities), to broaden this understanding, as such analyses lends to different perspectives and potential competitive scenario outcomes (Beaven et al., 2008). Individuality has not yet been well studied, and some key features that remain include how stable a response is (are responders always responders and vice versa for non-responders? does this differ with nature of the stimuli used?) and athlete age (the stress response in terms of cortisol does change with age?). However, individuality appears to be the major contributor to variability in outcome of different interventions.

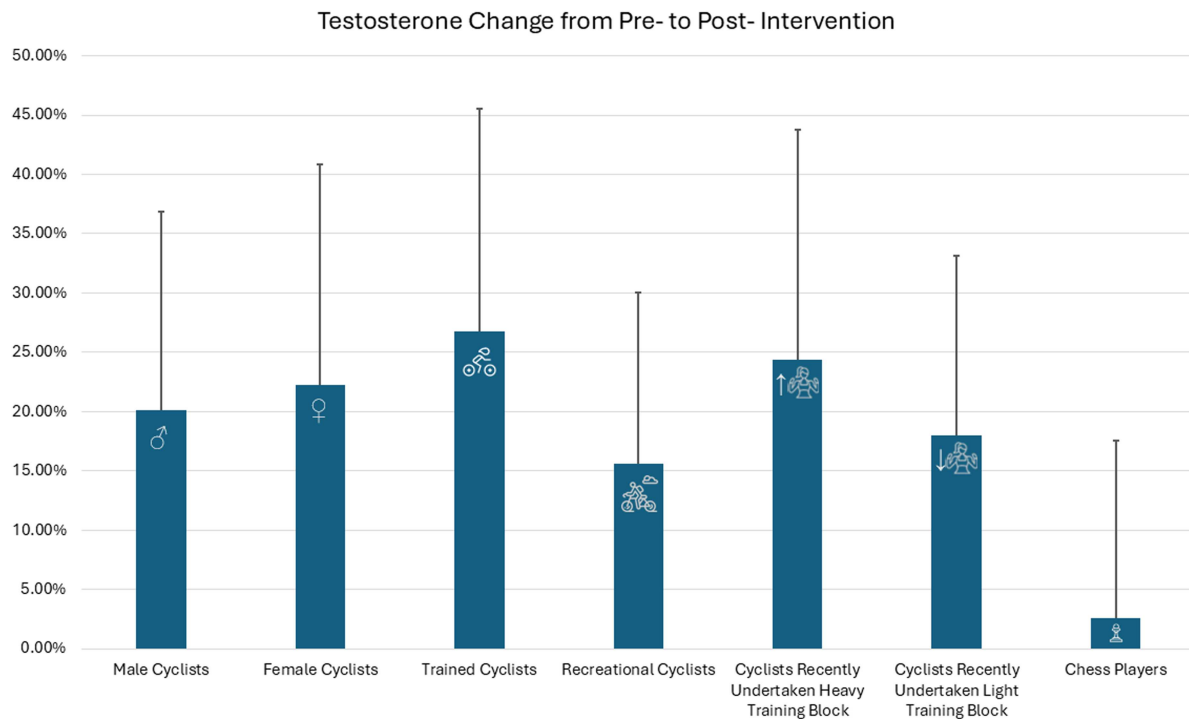


Figure 2. Example of testosterone change as a proportion of baseline $\pm$ standard deviation following the same treatment in cyclists vs. chess players adapted from studies elsewhere (Cook et al., 2021; Serpell et al., 2025). All participants completed the same exercise protocol, which required undertaking a short bout of intense exercise on a cycle ergometer (Wattbike, UK). The protocol consisted of repeated efforts (5×6 -s) interspersed with 60-s of recovery. The magnetic resistance was set at level 1 on the Wattbike, and fan resistance at level 3. Participants were instructed to work at an intensity where the rating of perceived exertion (RPE) was approximately 7 on a 1 to 10 scale, where 1 = very light intensity and 10 = maximum intensity. A low intensity (RPE = 3) warm-up of one minute was performed prior to commencing the physical stressor. Note, post treatment salivary testosterone for cyclists was measured 5-min post treatment, for chess players it was 15-min post treatment. Salivary testosterone change is thought to peak 15 to 20-min post stress exposure (Cook et al., 2021; Crewther et al., 2021). The male cyclist group consisted of trained and recreational male cyclists who had recently undertaken a “heavy” training block or a “light” training block. Similar for females. The trained/competitive cyclist group consisted of males and females who had recently undertaken a “heavy” training block or a “light” training block. Similar for the recreational cyclists group. The cyclists who had recently undertaken a “heavy” training block consisted of male and female competitive and recreational cyclists. Similar for cyclists who had recently undertaking a “light” training block.

Practical implications and concluding remarks

There is some reasonable evidence that the hormones cortisol and testosterone may be biomarkers of performance in both males and females. However, individuality may be a large sex-independent contributor, with some individuals being responders and others not. The mechanisms behind responsiveness may be a function of an individual's physiology, trained state, and/or how they perceive a given stressor. Furthermore, it may change with the type of stimulus used and over time.

Key factors that can influence stress responsiveness from a hormonal perspective appear to include age, current performance level of the athlete, trained state, lean muscle mass and baseline strength, menstrual cycles or use of certain hormone oral contraceptives (in some females), and perception of and likeability surrounding the stimulus used. In designing a sophisticated pre-event (e.g. training or competition) intervention, the nature of any stimulus chosen needs to account not only for these types of individual components but also for the concurrent needs of a realistic warm-up (e.g. a warm-up should “warm” muscles); a well-designed warm-up, for example, potentially assists both hormone “responders” and “non-responders.” The importance of achieving any hormone response needs to be situated in perspective to this.

Given that the effectiveness of stressors may be individual and training linked variable, and given fluctuating baseline hormones for females, the type of stimulus may need consideration; and substantially more data on individuality and variability is required. Furthermore, research exploring readiness in females from a hormonal perspective is limited. As such, given the nature of individuality in hormonal response to stress in females and males, and sex differences in baseline hormone concentration and responsiveness to stressors, opportunity exists to undertake further work in this area (i.e. sex differences and individuality) to enhance understanding and application of strategies for females and males to achieve best practice competition preparation.

Acknowledgements

None to declare.

Author contributions

CRedit: **Benjamin G. Serpell**: Conceptualization, Formal analysis, Investigation, Project administration, Resources, Software, Writing – original draft, Writing – review & editing; **Christian J. Cook**: Conceptualization, Project administration, Resources, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

None to declare.

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