

# Individual variation in the cortisol response to a simulated Olympic weightlifting competition is related to changes in future competitive performance

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**ABSTRACT:** The cortisol (C) and testosterone (T) responses to experimental stress have been linked to sport and health outcomes several days to years later. Here we examined the utility of these biomarkers, taken across a simulated Olympic weightlifting (OWL) competition, as predictors of future competitive performance in young athletes. Seventy junior athletes (46 males, 24 females) participated in a talent identification and development programme that replicated an OWL competition. Performance was indexed by the total load lifted, relative to body mass, with serum changes in C ( $\Delta C$ ) and T ( $\Delta T$ ) concentrations profiled. We identified each athlete's best performance in real competitions over two subsequent years via online resources. Hierarchical regression was used to predict changes in competitive performance at <12 ( $\Delta Total12$ ) and 12-24 months ( $\Delta Total24$ ). The simulated OWL event promoted a small positive  $\Delta C$  (effect size [ES]=0.3) and  $\Delta T$  (ES=0.5), but with large variation in  $\Delta C$  (-58% to 200%) and  $\Delta T$  (-21% to 71%). Performance improved after 12 (ES=1.5) and 24 months (ES=0.9). The  $\Delta C$  was negatively related to the  $\Delta Total12$  and  $\Delta Total24$  when controlling for competitions entered ( $R^2=13-24\%$ ). Sensitivity analyses confirmed the  $\Delta C$  link to both outcomes ( $R^2=9\%$ ). The serum C and T responses to a simulated OWL competition varied considerably between participants. Their competitive performance improved over the next two years and individual performance trajectories were related to the  $\Delta C$ . Therefore, individual variation in the C responses to a competitive stressor may help forecast the training and/or competitive gain process in young developing athletes.

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## INTRODUCTION

The hypothalamic-pituitary-adrenal (HPA) axis and hypothalamic-pituitary-gonadal (HPG) axis are two major neuroendocrine systems that coordinate the release of cortisol (C) and testosterone (T) into blood circulation; both key signals involved in human development and expression of performance [1, 2, 3]. In sport, the stressors imposed by exercise, training and competition can promote acute and/or chronic changes in C ( $\Delta C$ ) and T ( $\Delta T$ ) concentrations [1, 4, 5, 6, 7, 8]. Such changes in the hormonal milieu help support the structural and/or functional development of different physiological systems (e.g., behavioural, cognitive, neuromuscular, energetic) that underpin athletic performance and training adaptation [1, 9], and on timescales reflecting both genomic and non-genomic actions [1].

One important feature of hormonal activation under stress is large individual variation. For example, the individual  $\Delta C$  (e.g., -57% to 255%) and  $\Delta T$  (e.g., -67% to 126%) differed considerably during

Olympic weightlifting (OWL) competition [8, 10], despite exposure to similar physical and psychological loads. Personal factors can affect hormone release (e.g., age, life experiences, nutrition, training status) [1, 11]. Genetic factors are also potentially involved, as evidenced by twin similarities (intra-class correlation coefficients [ICC] >0.75) in the C response to exercise [12]. Others report some stability in the  $\Delta C$  across physical and psychosocial stressors [13], and  $\Delta T$  when performing different workouts [14]. These findings support the idea that C or T release under stress, if highly individual and stable over time, might reflect a phenotype that confers differential adaptations to identical stressors in sport [1].

Neuroendocrine studies endorse such a perspective, whereby the acute C responses to an experimental stressor predicted health-related trajectories in selected populations (e.g., police officers, soldiers) several months to years later [15, 16, 17]. Similarly, in team-sport

competition, a relationship emerged between the  $\Delta C$  and  $\Delta T$  to a physical stressor and subsequent win-loss outcomes several days later [18, 19]. To our knowledge, no studies have assessed whether these biomarkers can predict individual performance in athletic competition over one or more years. The sport of OWL would provide an ideal experimental model, with competition producing heterogeneous hormone responses and a quantifiable outcome (i.e., total load lifted). This research could add value in areas of talent identification, performance prognostics linked to biochemical changes, and individualisation of training programmes. Some control for time-of-day effects is however necessary, as the hormonal responses to strength-type exercise can vary across the day [4, 5].

This study investigated the serum C and T responses of young athletes to a simulated OWL competition, as predictive biomarkers of performance in real competition over two subsequent years. This timeframe was based on somewhat stable C responses to challenge (over 18 months) among children and youth [20], and similar results for athletes (ICC = 0.47) across real and simulated OWL competitions over a two-year period (unpublished data). Our first hypothesis was that C and T levels would rise across the simulated OWL competition, but with variable responses between athletes. The second hypothesis was that individual  $\Delta C$  and/or  $\Delta T$  would be related to changes in competitive performance at <12 and 12-24 months.

## MATERIALS AND METHODS

### *Participants*

Seventy-seven junior athletes were recruited for this study, but seven were removed from the final analysis due to a lack of follow-up data. The final cohort of males ( $n=46$ ) and females ( $n=24$ ) had a mean age ( $\pm$ SD) of  $18.0\pm 1.2$  and  $17.6\pm 1.2$  years, height of  $173\pm 8.4$  and  $163\pm 6.8$  cm, body mass (BM) of  $77.6\pm 17.0$  and  $65.9\pm 17.3$  kg, training experience of  $4.4\pm 1.1$  and  $4.4\pm 0.8$  years, and a personal best lift (combined total load) of  $231\pm 41.6$  and  $138\pm 28.6$  kg, respectively. Pre-screening revealed that the participants were healthy, injury-free, and not taking any doping agents. As registered athletes, they were routinely tested for illegal substances in and out of competition. One female did report using oral contraceptives, but her results were retained as they did not unduly bias any result. Given the testing format of this study (see below), we were unable to control for menstrual-phase differences between females, potentially affecting baseline T concentrations [21]. The expression of maximal strength does not appear to be influenced by menstrual phase [22, 23]. Written informed consent and parental consent were provided before study commencement. Ethical approval was provided by the Institute of Sport – National Research Institute, Poland.

### *Study design*

A quasi-experimental design with prospective monitoring was used to address the study hypotheses. The athletes were invited to participate in a national talent identification and development programme for weightlifters in Poland, where testing replicated somewhat an

OWL competition. This programme was scheduled over four consecutive days at the same indoor venue. Testing was conducted between 10 am and 1 pm to account for circadian variation in basal hormones, hormone responsiveness to exercise, and OWL performance itself [4, 5, 18, 24]. To ensure ecological validity, the athletes were instructed to maintain their normal dietary intake and to follow any established pre-competition routines (e.g., smelling salts, motivational feedback). They were also instructed to refrain from intense exercise (>2 days) before their assessment to reduce the confounding effects of muscle damage, oxidative and inflammatory responses [24, 25], and to get adequate sleep (>7 hours) to further eliminate any fatigue. As a national programme aimed at identifying and developing young talented weightlifters, we anticipated that some form of tapering schedule (e.g., a reduction in training volume) [8] would be adopted to ensure peak performance. The programme started within four days of the Polish age-group championships, so most athletes were still in the competitive phase of training.

Athlete testing was conducted in front of a small audience under International Weightlifting Federation rules (<http://www.iwf.net/>) with some modifications. Assessment began with a standard warm-up (15-20 minutes) using progressively heavier loads up to 90-93% of the first lift. Three single-lift trials were completed in the snatch and clean and jerk (CJ) exercises with the aim to lift the heaviest load possible. Between-trial rest periods were at least five minutes to reduce fatigue. For trained weightlifters, the snatch and CJ exercises are both highly reliable with coefficients of variation (CV) of <3% and ICC values >0.93. An independent judge was present to assess each lifting attempt as a success or failure. A failed attempt could be repeated by participants, but only if it occurred in the two initial trials. Weightlifting performance was indexed by the total combined load across the snatch and CJ exercises, as it determines the athlete's placing in their weight class [9]. The total load lifted was also used to indicate current physical capacity, as it approached (96% on average) each participant's personal best performance and both outcomes were strongly related ( $r=0.93$ ).

### *Hormone testing*

Two capillary blood samples were taken from each subject; before warming up and within five minutes of the last CJ attempt, equating to a sampling period of around 45 minutes. Logistical constraints (e.g., locality of room for blood collections) prevented us from sampling immediately after the last lift. Using a sterile lancet, a skin incision was made on the index finger of the non-dominant hand, after which a blood sample ( $\sim 300 \mu\text{L}$ ) was drawn and placed into a serum microvette (Greiner Vacuette, Germany) for clotting. After centrifugation, the supernatant was transferred to a labelled tube and stored at  $-80^\circ\text{C}$  for no longer than a month. The samples were assayed for T and C concentrations using enzyme-linked immunoassay kits (DRG, Germany). The lower detection limits for the T and C kits were  $0.3 \text{ nmol}\cdot\text{L}^{-1}$  and  $6 \text{ nmol}\cdot\text{L}^{-1}$ , respectively. The CVs for duplicate

samples were less than 4% and inter-assay kit CVs were less than 8%. For analysis, the pre- to post-competition  $\Delta C$  and  $\Delta T$  were calculated and then log transformed to approximate percentages.

### Monitoring competitive performance

Over the next two years, we monitored athlete performance (to nearest 1 kg) and their BM (to nearest 0.1 kg) during registered OWL competitions using two internet resources; the International Weightlifting Results Project (<http://www.iwrp.net>) and a Polish OWL website (<http://www.podnoszenieciezarow.pl/>). All results were cross-referenced to check for correctness and missing data. To account for seasonal fluctuations in maximal strength, only the best OWL performance in each 12-month block was analysed. If achieved more than once, the load lifted at a lighter BM was selected, as it represents greater relative strength. Performance was divided by BM (i.e.,  $\text{kg}\cdot\text{kg}^{-1}$ ) to account for body size differences between weight classes and sex [8, 9]. Data were further expressed as a log-transformed change score at <12 ( $\Delta\text{Total12}$ ) and 12-24 months ( $\Delta\text{Total24}$ ) from initial testing, again to approximate percentages. Since athletes can vary in their competitive frequency, we also recorded the number of competitions entered over the 12-month ( $M=6.1$ ,  $SD=2.9$ ) and 24-month periods ( $M=11.4$ ,  $SD=5.7$ ), with the latter representing cumulative frequency.

### Statistical analyses

All data were analysed using the R programming package. To assess hormone reactivity, we compared the  $\Delta C$  and  $\Delta T$  to a zero baseline and between sexes using a paired and unpaired T-test, respectively. Performance was examined with a two-way (Sex, Time) analysis of variance, followed by simple main effects and Tukey contrasts. Cohen's effect sizes (ES) were also computed with 95% confidence intervals (CI), as follows; <0.2 = trivial, 0.2 to <0.5 = small, 0.5 to <0.8 = medium, 0.8+ = large [18]. To predict changes in future OWL performance, a three-step hierarchical regression was employed with the  $\Delta\text{Total12}$  and  $\Delta\text{Total24}$  entered as dependant variables. Control variables were included in step one, once identified through a stepwise selection process using the Bayesian information

criterion. The control variables initially tested were participant age, sex (males=0, females=1), current physical capacity, training years (at best performance), and competitions entered. The  $\Delta C$  and  $\Delta T$  were added in step two, followed by the  $\Delta C \times \Delta T$  interaction in step three. Diagnostic testing revealed that all statistical assumptions were met. Significance was set at  $p \leq 0.05$  for all analyses.

## RESULTS

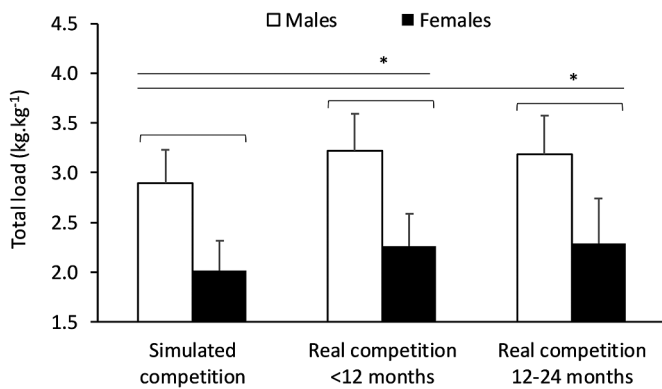
The raw hormone (Table 1) and performance (Figure 1) results are presented to aid interpretation. We found no sex differences in the  $\Delta C$  ( $p=0.494$ ) or  $\Delta T$  ( $p=0.937$ ) across the simulated OWL competition. A small positive  $\Delta C$  ( $ES=0.3$  [95% CI 0.0, 0.6]) and  $\Delta T$  ( $ES = 0.5$  [95% CI 0.1, 0.8]) emerged when data were pooled, though only the T result was significant (Table 1). On an individual level, the C and T responses (as a % from baseline) ranged from -58% to 200% and -21% to 71%, respectively. Exploratory testing with partial correlations (controlling for sex) identified several correlates of the  $\Delta C$ , but not  $\Delta T$ , including training experience ( $r=-0.29$ ), BM ( $r=0.25$ ), pre-competition T ( $r=0.31$ ) and C ( $r=-0.48$ ).

We observed a sex and time effect on OWL performance (both  $p < 0.001$ ), but no interaction ( $p=0.227$ ). Males ( $3.10 \pm 0.39 \text{ kg}\cdot\text{kg}^{-1}$ ) had greater relative strength ( $p < 0.001$ ) than females ( $2.19 \pm 0.38 \text{ kg}\cdot\text{kg}^{-1}$ ) with a large ES difference of 2.4 (95% CI 2.0, 2.8). Simple testing for a time effect ( $p < 0.001$ ) with post-hoc contrasts revealed improvements ( $p < 0.01$ ) in the  $\Delta\text{Total12}$  ( $2.89 \pm 0.58 \text{ kg}\cdot\text{kg}^{-1}$ ) and  $\Delta\text{Total24}$  ( $2.88 \pm 0.0.59 \text{ kg}\cdot\text{kg}^{-1}$ ) from the simulated event ( $2.60 \pm 0.53 \text{ kg}\cdot\text{kg}^{-1}$ ). These differences represent large ES changes of 1.5 (95% CI 1.1, 1.8) and 0.93 (95% CI 0.60, 1.30), or gains of  $11.4 \pm 7.7\%$  and  $10.8 \pm 11.6\%$ , respectively. The change in performance did not differ significantly between the two follow-up periods ( $ES=-0.1$  [95% CI -0.4, 0.3]). The individual performance changes in each 12-month block were strongly and positively correlated ( $r=0.71$ ,  $p < 0.001$ ) when controlling for sex.

The regression models are depicted in Table 2. To aid interpretation, all coefficients have been back-transformed into percentages. In step one, only competitions entered was selected as a control variable, explaining 13% and 17% of variation in the  $\Delta\text{Total12}$  and

**TABLE 1.** Serum hormone concentrations before and after the simulated Olympic weightlifting competition in young male ( $n=46$ ) and female ( $n=24$ ) athletes. Data are presented as means  $\pm$  SD.

Variable		Pre-competition	Post-competition	% change	p value
Cortisol ( $\text{nmol}\cdot\text{L}^{-1}$ )	Combined	435 $\pm$ 170	493 $\pm$ 198	11.2 $\pm$ 60.5	0.064
	Males	445 $\pm$ 164	487 $\pm$ 185		
	Females	414 $\pm$ 182	505 $\pm$ 226		
Testosterone ( $\text{nmol}\cdot\text{L}^{-1}$ )	Combined	11.7 $\pm$ 10.5	13.0 $\pm$ 13.2	7.1 $\pm$ 17.0	0.001
	Males	16.8 $\pm$ 9.50	18.8 $\pm$ 12.9		
	Females	1.86 $\pm$ 0.92	1.99 $\pm$ 0.96		



**FIG. 1.** Olympic weightlifting performance in the simulated competition and best performance during real competitions over two years in young male ( $n=46$ ) and female ( $n=24$ ) athletes. Data are presented as means  $\pm$  SD. \*Significant from the simulated competition  $p < 0.01$ .

$\Delta$ Total24, respectively. In step two, the  $\Delta$ C contributed to the  $\Delta$ Total12 ( $p=0.025$ ), whereby a 1% increase in C (as a log value) predicted a 0.04% decline in performance from the predicted group mean ( $\sim 8\%$ ) when controlling for competitions entered. Overall model fit tended to improve, but this was not statistically significant ( $p=0.069$ ). The  $\Delta$ C in step two also contributed to the  $\Delta$ Total24 ( $p=0.006$ ), such that a 1% increase in C predicted a 0.07% drop in performance from the mean response ( $\sim 2\%$ ), whilst improving model fit by 6.8% ( $p=0.022$ ). The  $\Delta$ C  $\times$   $\Delta$ T interactions (in step 3) were not significant predictors of performance when accounting for all other variables, nor did they enhance the fitted models ( $p > 0.505$ ).

To test the robustness of our results, sensitivity analyses were conducted by removing the control variable and retesting the  $\Delta$ T and  $\Delta$ C in a stepwise manner. This procedure confirmed the  $\Delta$ C as the only hormonal contributor to  $\Delta$ Total12 ( $B=-0.05$  [95% CI -0.08,

**TABLE 2.** Regression models predicting changes in Olympic weightlifting performance in real competitions.

Models	Dependent variable: $\Delta$ Total12					
	B	95% CI	B	95% CI	B	95% CI
<i>Step 1</i>						
Intercept	0.07 <sup>#</sup>	0.04, 0.10	0.08 <sup>#</sup>	0.05, 0.12	0.08 <sup>#</sup>	0.05, 0.12
Competitions	0.01 <sup>**</sup>	0.00, 0.02	0.01 <sup>**</sup>	0.00, 0.02	0.01 <sup>**</sup>	0.00, 0.02
<i>Step 2</i>						
$\Delta$ T			-0.04	-0.13, 0.07	-0.04	-0.13, 0.07
$\Delta$ C			-0.04 <sup>*</sup>	-0.07, -0.01	-0.03	-0.07, 0.00
<i>Step 3</i>						
$\Delta$ C $\times$ $\Delta$ T					-0.06	-0.24, 0.16
<i>Model fit</i>						
$R^2$	0.127 <sup>*</sup>		0.172 <sup>**</sup>		0.163 <sup>**</sup>	
$\Delta R^2$			0.044		-0.008	
Models	Dependent variable: $\Delta$ Total24					
	B	95% CI	B	95% CI	B	95% CI
<i>Step 1</i>						
Intercept	0.00	-0.05, 0.06	0.02	-0.04, 0.07	0.02	-0.04, 0.07
Competitions	0.01 <sup>#</sup>	0.01, 0.02	0.01 <sup>#</sup>	0.01, 0.02	0.01 <sup>#</sup>	0.01, 0.02
<i>Step 2</i>						
$\Delta$ T			-0.02	-0.15, 0.14	-0.01	-0.15, 0.14
$\Delta$ C			-0.07 <sup>**</sup>	-0.11, -0.02	-0.07 <sup>**</sup>	-0.12, -0.02
<i>Step 3</i>						
$\Delta$ C $\times$ $\Delta$ T					0.11	-0.18, 0.49
<i>Model fit</i>						
$R^2$	0.172 <sup>#</sup>		0.241 <sup>#</sup>		0.234 <sup>#</sup>	
$\Delta R^2$			0.068 <sup>*</sup>		-0.006	

Key:  $\Delta$ Total12 = change in performance at 12 months,  $\Delta$ Total24 = change in performance at 12-24 months,  $\Delta$ C = change in cortisol from pre- to post-competition,  $\Delta$ T = change in testosterone from pre- to post-competition. All coefficients have been back-transformed into percentages for interpretability. Significant at <sup>\*</sup> $p < 0.05$ , <sup>\*\*</sup> $p < 0.01$ , <sup>#</sup> $p < 0.001$ .

-0.01],  $R^2=8.6\%$ ,  $p=0.008$ ) and  $\Delta\text{Total24}$  ( $B=-0.07$  [95% CI -0.12, -0.02],  $R^2=9.1\%$ ,  $p=0.006$ ). We repeated these procedures with performance in the simulated OWL competition, as the dependant variable, and two control variables (i.e., gender, training experience). The  $\Delta\text{C}$  and/or  $\Delta\text{T}$  were not related to performance ( $p>0.136$ ) at any stage of analysis. Further testing also revealed no association between pre-competition C or T concentrations and OWL performance ( $p>0.475$ ).

### DISCUSSION

This study examined whether the acute T and C responses of young athletes, measured in a simulated competitive environment, would prospectively predict future performance in real competitions. Consistent with our first hypothesis, serum C and T concentrations increased (small ES) during initial testing with evidence of large individual variability. Weightlifting performance also improved (large ES) within a year and this level of performance was maintained in year two. Aligning to our second hypothesis, the individual C under competitive stress contributed to some variance in future OWL performance.

The study participants experienced a small positive  $\Delta\text{C}$  (11%) and  $\Delta\text{T}$  (7%) in the simulated OWL event. Unpublished data from another OWL cohort ( $n=9$ ) revealed a plasma volume shift of  $-14\pm 3\%$  in a comparable event; thus, our results could be partly attributed to a haemoconcentration effect. This cannot, however, explain the heterogeneity observed in this and other OWL studies [8, 10, 26]. Both hormones were unrelated ( $r<0.12$ ) to the total load lifted and, given that participants were habituated to training and competition, we can rule out any familiarisation effect. Heritable and reliable differences in HPA-axis reactivity to stress offers one explanation [12, 13, 20], with corroborating reliability data ( $\Delta\text{C ICC}=0.47$ ) on adults competing in OWL events over two years (unpublished). Since the  $\Delta\text{C}$  was related to pre-competition C and T concentrations in this work, more complex feedback mechanisms involving the HPG- and HPA-axes appear to be involved. Further research is still needed on younger athletes to assess hormone reliability across different stressors and time periods. In addition, other factors can affect stress-induced hormone reactivity (e.g., early life experiences, personality traits, social support, nutrition, training status) [1, 11]; thus, their assessment would add value when attempting to explicate the drivers of individual stress responses.

Weightlifting performance improved considerably ( $\sim 11\%$ ) within 12 months, especially when compared to gains ( $<3\%$ ) reported in other OWL studies [26, 27], before stabilising at 12-24 months. This difference can be attributed to athlete monitoring across a developmental period associated with normal gains in muscle size and strength [28, 29]. Notably, the  $\Delta\text{C}$  was related (negatively) to the  $\Delta\text{Total12}$  and  $\Delta\text{Total24}$  after controlling for other variables and when assessed in isolation via sensitivity analyses. Cortisol often correlates with OWL performance [7] and maximal strength [6, 30], with recent work showing that mid-week  $\Delta\text{C}$  can discriminate win-loss outcomes

in professional rugby matches [18]. In other domains, the C response to an experimental stressor predicted health indices (e.g., resilience, depressive symptoms) on follow-up periods of six [17], 12 [16] and 48 months [15]. Whilst interpretation is complicated by other factors (e.g., stressor intensity, population tested), including both adaptive and maladaptive outcomes, this work highlights the potential of this dynamic C measure in predicting health-related trajectories. Given that performance did not improve further after 12 months in this study, and the positive correlation between individual trajectories in both follow-up periods, hormonal assessment (under competitive conditions) at a two-yearly interval would be a feasible approach for athlete testing.

Maximum growth rate amongst young athletes generally occurs at 12-15 years of age, before gradually declining into late adolescence [3]. Our BM data paralleled this trend, increasing within 12 months before stabilising at 12-24 months, as did OWL performance when normalised for BM. Hence, both neurological and morphological pathways are likely contributors to the observed strength changes [27, 31], potentially arising from training factors and/or natural maturation processes. Different maturity features (e.g., muscle size, sexual development) are thought to be controlled by the HPG- and HPA-axes [3]; thus, it's conceivable that acute C responsiveness to a stressor might operate as an intermediate signal that reflects adaptive potential during a key developmental period. Alternatively, the  $\Delta\text{C}$  could reflect prior training exposure, as it correlated with training experience at study onset, and one that carries over to future gains (or losses) in competitive OWL performance. Others suggest that individual C responses might reflect differential adaptations to sport-related [1] or broader life stressors [17], or it could represent a preparative action (of glucocorticoids) for impending stress [2].

It was somewhat surprising that the  $\Delta\text{T}$  was a poor predictor of the  $\Delta\text{Total12}$  and  $\Delta\text{Total24}$ . This may well be a function of more complex release patterns. The release of T prior to, and after, a competitive encounter is thought to depend on social factors (e.g., mood, outcome anticipation) [32] driven by personal expectations, situational and environmental cues. As such, the utility of T could be realised over a shorter (3-4 days) time span in competitive sport [19]. Conversely, T might have some prognostic value of physical efforts over longer timeframes (i.e., a rugby game) when dominant behaviours are required [33], rather than brief maximal strength-based activities like OWL, where neural factors like intra- and inter-muscular coordination might predominate [31]. No performance linkages emerged when testing the  $\Delta\text{C} \times \Delta\text{T}$  interaction. This interplay is perhaps a feature of acute settings where hormones are thought to contribute to flexible adjustments in OWL performance [10] and, to date, has only been demonstrated in male cohorts [10, 34].

Recent work on weightlifters highlighted the importance of muscle damage (e.g., creatine kinase), oxidative (e.g., malondialdehyde), and inflammatory (e.g., C-reactive protein) markers in describing exercise stress, as well as interactions between these biomarkers [24, 25]. The interrelationship between these outcomes

and competition-induced activation of the HPG- and HPA-axes, including possible time-of-day effects on hormones and OWL performance [4, 5, 24], are worthwhile pursuits to help explain our results. The protocols used to simulate an OWL competition is another consideration when interpreting our results. Some modifications were necessary to accommodate the large number of participants within a short time span. For example, to ensure compliance and increase our sample size, participants were assessed as they became available. Hence, we tested small groups who may differ in weight category, which required different starting and incremental loads. For convenience athletes were also tested in a set order, irrespective of successes or failures, thereby contributing to a slightly longer (5-minute) rest period between the final two trials per exercise.

Other study limitations must be recognised, for example, the regression models only explained a small proportion of OWL performance. Moreover, we did not have access to athlete training loads and training structure over the experimental period, nor other information (e.g., dietary intake, illness or injuries) that could illuminate the unexplained variance. Still, profiling individual C dynamics might provide a useful adjunct to available training information, when up to 9% of performance variability could be explained by this biomarker. Sex-related differences in T production and muscle strength trajectories [28, 29] are other confounds in longitudinal studies on athletes, which was partly addressed by examining percentage

changes in the study outcomes. Psychological factors (e.g., motivation, self-esteem) might also predict OWL performance [35], and we were unable to control for menstrual-related T fluctuations and its impact on female motivation [21]. Conversely, the basal and exercise activation of C is unaffected by the menstrual cycle [36, 37].

## CONCLUSIONS

In summary, the serum C and T responses to a simulated OWL competition showed considerable variability between young athletes. Cohort monitoring over the next two years revealed improvements in competitive OWL performance and the individual  $\Delta C$  predicted a small proportion of performance trajectories. This suggests that individual variation in C responsiveness to a competitive stressor may forecast, in some capacity, the training process and/or competitive outcomes of young developing athletes.

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## Conflicts of interest

The authors declare that they have no conflicts of interest.

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