Serum cortisol as a moderator of the relationship between serum testosterone and Olympic weightlifting performance in real and simulated competitions

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ABSTRACT: Some equivocality exists regarding the effect of testosterone (T) on competitive performance with cortisol (C) implicated as a moderating factor. This study investigated whether C is moderating the T relationship with Olympic weightlifting (OWL) performance during real and simulated competitions. We monitored 105 male athletes (age 19.3±3.7 years); 46 during real OWL competitions (e.g., national age championships) and 59 across simulated events (e.g., talent identification). Serum T and C were assessed before warming up and within 15 minutes of event completion. Performance was indexed by the total combined load across the snatch and clean and jerk exercises. Hierarchical linear regression and simple slopes were employed to test the hormone and performance relationships. Pre-competition T (pre-T) and C (pre-C) were unrelated to OWL performance when controlling for competition type, time of day, age, and body mass (model=75.6% variance). However, the pre-T × pre-C interaction was significant (model=77% variance). Upon exploring this interaction, different pre-T and performance relationships emerged for males with high pre-C (β=-9.96) and low pre-C levels (β=9.04), with diverging slopes (p=0.006). The assessment of T changes and pre-C produced similar results. The association between male T and performance during OWL competition was determined by C activity, which could explain conflicting reports of T as a correlate of competitive abilities. Our results imply that T and C are not strictly anabolic and catabolic biomarkers of performance, respectively, but rather they exert complementary actions that could depend on task, situational and environmental needs.

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INTRODUCTION

In sport, testosterone (T) is a recognised androgen producing both androgenic (i.e., reproductive function) and anabolic (i.e., skeletal muscle and bone development) effects [1]. These actions predominate during puberty when T production increases dramatically (up to 20-fold), particularly among boys [2, 3]. In adult populations, acute physiological T changes appear less important for promoting muscle size and strength gains [4], although T may remain permissive to hypertrophy. Still, T has been implicated in other neuromuscular functions (e.g., mood, motivation, cognition, neural activity) that support human movement [5], as alternative pathways to explain its training role in a physiological range.

Several studies have reported a link between T and athlete (male or female) performance in sporting competition [6, 7, 8, 9, 10], but these relationships include pre- and post-competition T measures, so it's unclear if T availability is driving performance, or whether it simply responds to exercise as a biomarker of stress. Conversely, other researchers have failed to find a T association with competitive performance [11, 12, 13, 14]. The pleiotropic effects of T on the neuromuscular system could explain these inconsistencies, such that some sports may preferentially utilise those T-related functions more so than others. Alternatively, some athletes might express certain features that enables them to better use T as a training resource, such as greater maximal strength [15, 16] or a higher training status [17].

Cortisol (C) is a glucocorticoid released under stress to mobilise energy resources [5], with recent evidence suggesting a further role as a moderator of T activity [18, 19, 20]. For instance, salivary T did not initially correlate with social status among women athletes [18] and hand-grip strength in healthy men [19]. However, significant relationships did emerge when individuals with relatively high C or low C levels were considered separately [18, 19]. Thus, simple bivariate associations could mask the presence of more intricate, and possibly functionally relevant, hormonal interactions. In fact, it transpired that the combination of low T and high C levels was associated with greater hand-grip strength before stressful

exercise [19]. This aligns to reports that rising C levels are necessary for optimising muscle strength under competitive stress and more so than T [14, 21]. To date, no work has examined this T and C interplay with respect to strength-based performance in competition.

This study investigated whether serum C activity is moderating the relationship between serum T and Olympic weightlifting (OWL) performance during competition. Only male athletes were recruited and, since moderation studies require larger samples (>10 subjects for each predictor), data from real and simulated competitions were collated for analysis. We hypothesised that T would be a poor (non-significant) predictor of the individual variances in OWL performance; however, a significant T × C interaction would emerge in relation to this outcome, as statistical evidence of moderation [22]. Based on prior work [19], we also hypothesised that T would be negatively related to performance, but only for those athletes with relatively high C levels before competition.

MATERIALS AND METHODS

Participants

One hundred and nine male weightlifters were tested, as part of a broad 10-year scientific monitoring programme conducted by the Institute of Sport – National Research Institute, Poland. These athletes participated in weight classes ranging from 50 kg up to +94 kg across youth (<17 years, n=27), and from 56 kg up to +105 kg across junior (<20 years, n=53) and adult (20+ years, n=29) competitions (http://www.iwf.net/). Body mass (BM) was measured to the nearest 0.1 kg during event weigh-in using electronic scales. All athletes were screened for any injuries, medical conditions, or other health issues that would confound the study results. The athletes were also questioned about anabolic doping agents, but none were reported, and they were routinely tested in this capacity in and out of competition. No athletes tested were currently banned for taking any illegal substances. Still, four subjects were removed from the final analysis due to serum T levels that exceeded the upper reference value (~46 nmol·L^{-1}) for healthy, non-obese men [23]. The final assessed cohort (n=105) had a mean age (±SD) of 19.3±3.7 years, BM of 81.4±21.0 kg, and training experience of 5.5±3.4 years. Written informed consent and parental consent, where necessary, was given before testing commenced. This experiment received ethical approval from the Institute of Sport.

Competition testing

Forty-six athletes were monitored during real competitions (i.e., registered club events, national age-group championships) and 59 across simulated events (i.e., national talent identification programme, preparation for a European championship). Testing was conducted under International Weightlifting Federation rules (http://www.iwf.net/). Briefly, three trials for both the snatch and clean and jerk (CJ) exercises were completed. Familiarisation was not necessary, as both exercises are very reliable among well-trained weightlifters with coefficients of variation (CV) of 2.3-2.7% [24]. A failed lift could be repeated, but only if this occurred on the first or second trials. The rest periods exceeded five minutes, except when consecutive lifts were required, and a two-minute rest period was imposed. Performance was indexed by the total combined load, calculated from the sum of the heaviest snatch and CJ lifts [14, 25], as it ultimately determines the athlete's placing in their weight class [26]. Though the CJ enables heavier loads (by 18-20%) to be lifted than the snatch [26], both exercises are strongly related to each other (r=0.97) and the combined total (r=0.99). All athletes completed a warm-up (15-30 minutes) using progressively heavier loads up to 90-93% of the first exercise trial.

To ensure ecological validity, we encouraged a normal dietary intake and maintenance of established pre-competition routines (e.g., smelling salts, motivational feedback). The athletes were instructed to get at least seven hours of sleep and they reported being awake at least three hours before testing, thereby accounting for the C awakening response [27]. The start times did vary across weight classes (10:00 am to 7:00 pm), as most competitions use only a single lifting platform, which can influence performance, perceived exertion and hormones [12, 28]. Weight class testing (in real competitions) also lasted ~60-120 minutes, depending on the number entries, whilst the simulated events were completed within an hour. Subsequently, we controlled for the type of competition and time-of-day in the statistical analyses (see below). All testing was performed in front of an audience (e.g., other athletes, coaches, family), so the environmental stressors would be somewhat comparable. To ensure peak performance, we anticipated that the athletes would follow some form of tapering schedule (e.g., a reduction in training volume) [12, 21, 25] several days before their individual assessments.

Blood hormone testing

Capillary blood provides a valid, non-invasive alternative to the venous assessment of T and C concentrations [29, 30]. Samples were taken before warming up, representing the pre-competition T (pre-T)

Table 1. Performance and hormonal profiles (means±SD) of male athletes combined across the real and simulated Olympic weightlifting competitions.

Variables		Mean	SD
Performance (kg)		257	64.5
Testosterone (nmol·L^{-1})	Pre-competition	15.4	6.2
	Post-competition	16.5*	6.5
	Δ score	1.2	4.1
Cortisol (nmol·L^{-1})	Pre-competition	426	146
	Post-competition	512*	170
	Δ score	85.4	179

Key: *Significant from pre-competition p<0.05.

and C (pre-C) measures, and within 15 minutes of event completion, signifying the post-competition T and C responses. Pre- to post-competition changes in T (TΔ) and C (CΔ) were also calculated. The sampling procedures were as follows; a small skin incision was made on the fingertip using a sterile lancet, after which a small volume of blood (~300 μL) was collected in serum microvettes (Sarstedt, Germany), placed on ice and centrifuged within 60 minutes. The supernatant was transferred to a labelled tube and stored at -80˚C before assay. All samples were assayed within two months using enzyme-linked immunoassay kits from the same manufacturer (DRG, Germany). The low standards for the T and C kits were 0.69 nmol·L^{-1} and 5.5 nmol·L^{-1}, respectively. The CVs for duplicate samples were less than 4% and inter-assay kit CVs less than 8%.

Statistical analyses

Before analysis, the hormonal variables, age, and BM were log-transformed to meet diagnostic assumptions. We first assessed the pre- to post-competition changes in T and C levels using a paired T-test. To aid interpretation, the raw hormonal data are presented. The primary analysis involved a three-step multiple hierarchical regression with OWL performance as the dependant variable. The type of competition, time of day, age, and BM were entered as control variables in Step one; pre-T and pre-C as predictors in Step two; and the pre-T × pre-C interaction in Step three. Training experience was omitted as a control variable, because it was strongly related (r=0.87) to subject age. All continuous variables were standardised to reduce multicollinearity and aid interpretation (i.e., coefficients expressed in SDs), whereas the type of competition was binary coded (real =0, simulated =1). The interaction terms were calculated by multiplying the standardized scores. Following a significant interaction, simple slopes were employed to graphically interpret the result at one SD above and below the mean [22]. The significance level was set at $p<0.05$.

RESULTS

The performance and hormonal data for the study population (pooled across all competitions) are reported in Table 1. A pre- to post-competition rise in both T ($p=0.003$) and C ($p<0.001$) levels emerged, representing small effect size changes of 0.20 and 0.48, respectively. Further testing revealed no significant differences in OWL performance or any hormonal variable between the real and simulated competitions. Those athletes participating in real events were

TABLE 2. Regression models predicting male Olympic weightlifting performance from pre-competition hormones.

	Model summaries	β	SE	t value	Adjusted R^2	ΔR^2
Step one	F(4, 100) = 83.4***				0.7602	0.7602
	Type of competition	-12.1	6.9	-1.74		
	Time of day	10.8	3.4	3.21**		
	Age	30.2	3.5	8.58***		
	BM	36.7	3.3	11.1***		
Step two	F(2, 98) = 54.8***				0.7564	-0.004*
	Type of competition	-12.6	7.0	-1.80		
	Time of day	10.8	3.4	3.19**		
	Age	30.2	3.6	8.34***		
	BM	37.5	3.6	10.6***		
	Pre-T	0.95	3.3	0.29		
	Pre-C	1.97	3.3	0.60		
Step three	F(1, 97) = 50.9***				0.7704	0.014
	Type of competition	-13.7	6.8	-2.00*		
	Time of day	12.6	3.4	3.76***		
	Age	29.2	3.5	8.27***		
	BM	39.2	3.5	11.2***		
	Pre-T	-0.46	3.2	-0.14		
	Pre-C	3.13	3.2	0.98		
	Pre-T × Pre-C	-9.50	3.6	-2.64**		

Key: BM = body mass, pre-T = pre-competition testosterone, pre-C = pre-competition cortisol. Level of significance *p<0.05, **p<0.01, ***p<0.001.

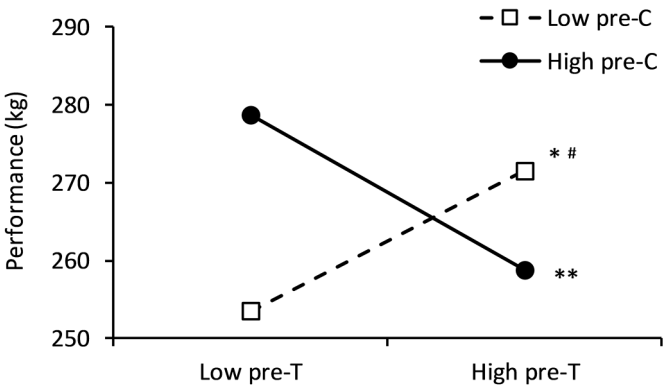

Fig. 1. Interaction between pre-competition cortisol (pre-C) and testosterone (pre-T) in relation to Olympic weightlifting performance. Slope is significant from zero *p<0.05, **p<0.06, Significant between-slope difference #p<0.05.

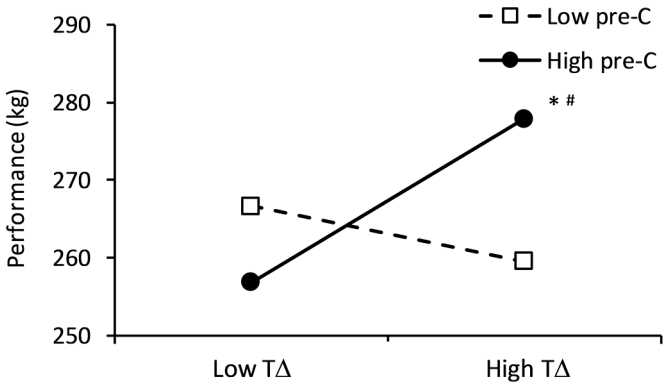

FIG. 2. Interaction between pre-competition cortisol (pre-C) and the testosterone changes (TΔ) in relation to Olympic weightlifting performance. Slope is significant from zero *p<0.05, Significant between-slope difference #p<0.05.

however younger (18.1±2.5 years) with lower BM (76.4±19.3 kg) and less training experience (4.3±2.2 years) than those athletes tested under simulated conditions (age 20.2±4.2 years, BM 85.3±21.5 kg, training experience 6.4±3.9 years) (all p<0.03).

The regression results are presented in Table 2. All control variables (except the type of competition) contributed significantly to the Step one model and accounted for 76.0% of the variation in OWL performance. In Step two, both pre-T and pre-C were unrelated (p>0.5) to performance, with no change in overall model fit when controlling for all other variables. Adding the pre-T × pre-C interaction in Step three explained an additional 1.4% of the variability in OWL performance and this change was significant (p=0.010). Two different slope patterns were revealed when deconstructing this interaction (Figure 1). The pre-T relationship with OWL performance was negative in athletes with relatively high pre-C levels (β=-10.0, SE=5.2, p=0.059), but positive among athletes with low pre-C levels (β=9.0, SE=4.4, p=0.044). These slope patterns also differed from each other (p=0.006).

This process was repeated for all permutations of pre-T, pre-C, TΔ, and CΔ. Parallel results (as above) were achieved when examining TΔ as a predictor and pre-C as a moderator. The Step one model is identical to that described above. In Step two, $F(2, 98) = 55.4$, $p<0.001$, the TΔ and pre-C measures did not contribute to the variance in OWL performance (p>0.3) with no significant change in model fit. When the TΔ × pre-C interaction was added in Step three, $F(1, 97) = 49.3$, $p<0.001$, this explained an additional 0.6% of the performance variability and the change in model fit trended towards significance (p=0.060). Upon exploring this interaction (Figure 2), we again found divergent slope patterns. The TΔ and performance relationship was positive among males with high pre-C levels (β =10.5, SE=5.1, p=0.042). Although these variables were unrelated among males with relatively low pre-C levels (β=-3.6, SE=4.7, p=0.456), the two slopes were different (p=0.045).

DISCUSSION

This study explored the relationship between serum T and competitive OWL performance with serum C as a moderating variable. Two findings support our initial hypotheses. First, pre-T concentrations were unrelated to OWL performance when controlling for all other variables, but the pre-T × pre-C interaction was a significant contributor to the model explaining the individual variances in performance. Second, exploring this interaction revealed divergent pre-T and performance relationships for athletes with high and low pre-C levels. The assessment of TΔ and pre-C revealed somewhat parallel results.

The blood T concentrations of males before any OWL competition, including the TΔ across each event, were unrelated to weightlifting performance. Many studies on trained male populations have also failed to find a T relationship with performance during OWL or powerlifting competition [13, 14, 25], and other sporting (e.g., judo, triathlon) events [11, 12]. These findings could reflect the relative contribution of those neuromuscular functions (e.g., mood, motivation, cognition, neural activity) supported by T [5], or simply different physical, technical and/or tactical measures used to assess competitive ability. Research interpretation is still limited by the common practice of simple bivariate comparisons and typically on smaller (<30 athletes), and sometimes mixed, population samples. We addressed these issues by examining a large cohort of male weightlifters under similar competitive conditions, whilst considering the T effect on a discrete performance outcome at different C levels. Subsequently, more complex hormonal interactions emerged that might be governing certain aspects of physical ability during sporting competition.

For the high pre-C group, better performance was achieved when T levels were low before competition (Figure 1) and the TΔ were high (Figure 2). This reversal in the high pre-C group was identified previously [19] and might reflect a ceiling effect of baseline T on T reactivity. Conversely, the low pre-C group performed better when T levels were high before competition (Figure 1). Accumulating evidence confirms that C can moderate the T effect on physical or psychological outcomes in sport and exercise [18, 19, 20], as well as T reactivity to competition [31]. One study found no evidence of this hormonal interplay during judo competition [8]; however, this work was likely underpowered (sample size of 28) for detecting a statistical interaction. Thus, examining T and C interactions could provide new insight for researchers and coaches by revealing relationships that are masked by simple (pooled) correlations. If rapid blood testing is available, samples analysed before a competition would provide a stronger basis for prescribing a hormonal priming strategy (e.g., videos, coach feedback) to enhance performance [32]. Other sources of hormonal variation (e.g., social environment, time of day) could also be exploited to optimise OWL performance, especially if the relationships described are stable over time.

Although the final regression models explained up to 77% of OWL performance, the hormonal interactions contributed to only 0.6% to 1.4% of this variance. This contribution was possibly diminished by controlling for several situational and demographic factors with a reported impact on OWL performance [14, 21, 25, 28]. Nevertheless, most weightlifters tested were competitive at a national and/or international level (i.e., elites) and enhancements of as little as 1.2% are deemed practically significant for this population [24]. By design, this study focused on serum T and C as trait variables, but these hormones also exhibit large within-subject variation that correlate to changes in training motivation [17, 33, 34] and muscle strength [15, 35], particularly among well-trained or physically-stronger athletes. Speculatively, both sources of hormonal variation and their interactions may allow more flexible responses or performance adjustments among individual athletes, depending on task, situational and environmental cues. Since female T levels show marked variation across the menstrual cycle, by eliteness and oral contraceptive use [34, 36], it would be prudent to test if the moderating effect on T is similar to men, and vary across these states.

Several mechanisms could explain these C and T linkages, as possible intermediaries to physical performance. For example, C can interact with androgen receptors [37] to modify the actions of T at target tissue. On a functional level, C can moderate the T relationship to status-relevant behaviours (e.g., aggression, dominance) [38, 39, 40] and anger-induced brain activity [41]. Parallel associations were observed regarding social status [18] and social positioning among athletes [20]. Both steroids might also form part of the pre-exercise arousal response via the sympathoadrenal system [14, 42], which has a direct impact on muscle force production. Adding to these complexities, reciprocal signalling between the hypothalamic–pituitary–adrenal and hypothalamic–pituitary–gonadal axes can jointly regulate C and T release, respectively [43]. This multifaceted network, with hormones acting as chemical signals, could explain the inconsistent relationships in sport. In fact, individuals within a homogenous cohort might achieve the same outcomes by somewhat "opposing" hormonal signals, as we demonstrated. We therefore suggest that T and C are not strictly anabolic and catabolic markers of performance, respectively, but rather they work in tandem to regulate several physiological systems that unpin (or reflect) physical performance.

The current results must still be balanced against the cross-sectional study design, which only implies cause and effect. In addition, we tested a convenience sample of athletes participating in several OWL competitions. As such, we had little control over the time of testing for each athlete, with the prior scheduling of weight classes at different times (during real events) introducing further bias. On the other hand, exploratory analyses revealed no significant time-of-day relationships with pre-T ($r=-0.10$), pre-C ($r=-0.04$), TΔ ($r=0.16$), and CΔ ($r=0.03$). Only performance was linked ($p<0.05$) to testing time, but this was a weak association ($r=0.35$) that was controlled for across each regression model. The lack of non-exercising data and androgen receptor measures are other study limitations, though this does not detract from our primary aim to unravel the T-performance relationship in a competitive setting.

It's also important to recognise that the majority (74%) of male weightlifters were under 20 years of age when assessed; therefore, maturation factors (e.g., sexual maturation, muscle mass) could play some role. However, these factors tend to covary with age-related changes in BM and T [25], and sub-group testing revealed that BM was strongly related ($r^2=88\%$) to lean muscle mass. Also, we did not monitor dietary restrictions, as practised by weight-classed athletes, but this does not appear to influence absolute OWL performance, pre- (weigh-in) and post-competition salivary C [44]. As a further limitation, OWL is a highly technical event so applications to other sports, particularly those that are more aggressive and less technical, are somewhat limited. Notwithstanding these caveats, the study cohort did span a wide age range (15-35 years) with varying body size (50-150 kg) and OWL abilities (142-424 kg), so our results are representative of most male Olympic weightlifters, and potentially of single acute strength-power movements.

In summary, the serum T relationship with OWL performance under competitive conditions was influenced by serum C activity. This could explain the conflicting reports of T as a performance correlate in sport, since most studies examine only bivariate relationships between these variables. Our work also implies that T and C are not strictly anabolic and catabolic markers of performance, respectively, but rather they exert complementary actions that could depend on the task, situational and environmental needs of athletes.

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