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ORIGINAL ARTICLE

Temporal Dynamics of Autonomic Nervous System Responses and Hormonal Balance after High-Load Effort in Weightlifters

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ABSTRACT

This study analyzed the synchronized temporal dynamics of autonomic nervous system (ANS) responses and hormonal balance following high-load weightlifting in trained athletes. A repeated-measures design was employed with 16 weightlifters who completed a session at 85–90% of their one-repetition maximum (1RM), including the snatch and clean and jerk. Heart rate variability (HRV) indices (RMSSD and LF/HF), testosterone (T), cortisol (C), and the T/C ratio were measured at four intervals: pre-exercise, immediately post-exercise, 30 minutes post-exercise, and 24 hours post-exercise. Findings indicated a significant decrease in RMSSD and an increase in LF/HF immediately post-exercise, reflecting acute sympathetic dominance. These levels showed gradual recovery within 30 minutes and near-complete restoration by 24 hours. Cortisol increased significantly post-exercise and remained elevated at 30 minutes before returning to baseline at 24 hours; however, testosterone levels remained stable. This resulted in a transient reduction in the T/C ratio, indicating a short-term catabolic shift. Correlation analysis revealed an inverse relationship between RMSSD and cortisol, and a positive relationship between RMSSD and the T/C ratio, confirming functional integration between autonomic regulation and the HPA axis. High-load weightlifting produces an acute, adaptive neurohormonal response. Complete recovery within 24 hours suggests the training load was within an optimal physiological range. These findings underscore the value of integrating HRV and hormonal markers to monitor training loads and recovery in elite strength sports.

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1- INTRODUCTION

Exercise physiology is one of the fundamental fields in sport sciences, as it is concerned with studying the physiological changes that occur in the body's systems in response to intense physical effort. High-load weightlifting is considered one of the most powerful forms of resistance effort, as it can induce acute and complex responses in the body's regulatory systems, particularly the autonomic nervous system and the hormonal system [1]. Studies have indicated that this type of effort causes immediate changes in sympathetic and parasympathetic activity, thereby affecting the stability of cardiovascular function [2].

Heart rate variability (HRV) is one of the most important indicators used to evaluate autonomic nervous system balance, as it reflects the interaction between sympathetic and parasympathetic activity during and after physical effort [3]. Plews et al [4] reported that high-load resistance exercise leads to a temporary reduction in parasympathetic activity with an increase in sympathetic activity, and that this pattern persists partially during the early phases of recovery. These findings confirm that tracking the temporal dynamics of HRV indicators may provide a better understanding of nervous system responses to physiological stress. On the other hand, anabolic and catabolic hormones, particularly testosterone and cortisol, play a pivotal role in regulating the body's anabolic–catabolic balance [5]. Recent studies indicate that high-load resistance effort increases cortisol levels, with only limited changes in testosterone, which is negatively reflected in the testosterone-to-cortisol ratio (T/C ratio) and affects the body's capacity for recovery [6]. Nevertheless, the temporal dynamics of these hormonal changes during the early recovery period have not been sufficiently examined [7, 8].

Despite the number of studies that have addressed either the autonomic nervous system or hormonal balance separately, studies that combine the synchronized temporal dynamics of both following high-load weightlifting effort remain limited. This shortage leaves a knowledge gap in understanding the integrative relationship between the autonomic nervous system and the hormonal system during the early stages of recovery, which constitutes the present research problem.

The aim of this study was to track the synchronized temporal dynamics of the neurohormonal response following high-load weightlifting effort in trained athletes. By monitoring heart rate variability (HRV) and hormonal markers (testosterone and cortisol), the researchers sought to identify how the autonomic nervous system and the endocrine system integrate during the acute stress and early recovery phases. The investigation specifically focused on whether these indicators reflect a functional pattern of physiological adaptation and restoration within 24 hours post-exercise. Ultimately, the study intended to provide a deeper understanding of the mechanisms of stress resulting from elite strength training to help optimize the monitoring of training loads and recovery.

2- MATERIALS AND METHODS

2.1 Study Design

An experimental approach in exercise physiology was used, adopting a repeated-measures design to track the temporal dynamics of autonomic nervous system response and hormonal balance following the performance of high-load weightlifting effort. The dependent variables were measured at four successive time points: the pre-test before effort, the immediate post-test after completion of the effort, the measurement after 30 minutes, and finally the measurement after 24 hours. This allowed the analysis of acute physiological responses and early recovery stages in an integrated temporal manner.

The study procedures were approved by the Ethics Committee of the College of Physical Education and Sport Sciences, University of Baghdad, in accordance with the principles of the Declaration of Helsinki for research involving human participants. All participants also signed an informed consent form before the start of the measurement procedures.

2.2 Study Sample

The study sample consisted of weightlifters from the Army Sports Club, selected purposively. The sample included 16 weightlifters. The sample was drawn from a single club to ensure homogeneity of training level and to reduce inter-individual variability. The sample met the following criteria: Training experience of no less than 3–5 years in weightlifting, in order to ensure stable physiological adaptations resulting from long-term training [9]. There is regular participation in high intensity resistance training. Free from muscular or neurological injuries during the previous six months. No use of supplements or hormonally active substances during the study period.

Table (1): Characteristics of the research sample

Statistical Measures / Variables	Mean	Standard Deviation	Median	Skewness Coefficient
Age (years)	**24.8**	**3.1**	**25.0**	**-0.21**
Body mass (kg)	**81.6**	**7.4**	**82.0**	**0.18**
Height (cm)	**178.9**	**5.6**	**179.0**	**-0.12**
Training experience (years)	**6.4**	**1.8**	**6.0**	**0.27**
Resting heart rate (beats/min)	**68.7**	**5.2**	**69.0**	**0.09**

Skewness coefficients ranging between −1 and +1 indicate an acceptable normality of the sample data distribution. The results presented in Table (1) indicate that the sample members demonstrate a high degree of relative homogeneity in anthropometric and training characteristics.

2.3 Research Tests

2.3.1 Heart Rate Variability Index (RMSSD) (Root Mean Square of Successive Differences). Measurement method: [10].

RMSSD was measured as a time-domain indicator of parasympathetic nervous system activity through recording cardiac R–R intervals using a portable electrocardiographic device (Polar H10) connected to HRV analysis software.

The measurement was performed over continuous five-minute duration with the subjects in a quiet, supine position within a temperature-controlled environment (22–24°C). Prior to the session, weightlifters were instructed to refrain from both caffeine consumption and physical exercise for 24 hours to ensure baseline stability. Data processing was conducted using the latest version of Kubios HRV software, which included the application of a medium artifact correction filter. Finally, RMSSD was extracted from the time domain for subsequent analysis [11].

The guidelines recommend that a 5-minute HRV recording in a stable position is a gold standard for analyzing time-domain indicators such as RMSSD.

2.3.2 Ratio of low-frequency spectral power to high-frequency spectral power

LF/HF (Low Frequency / High Frequency) Ratio

The LF/HF ratio was derived from a frequency-spectrum analysis of heart rate variability (HRV) signals using a Fast Fourier Transform (FFT) applied to the same 5-minute recordings utilized for RMSSD extraction. This frequency analysis was performed using Kubios HRV software, with the Low Frequency (LF) range defined as 0.04–0.15 Hz and the High Frequency (HF) range defined as 0.15–0.40 Hz. Ultimately, the LF/HF ratio was calculated to serve as a physiological indicator of relative sympathetic dominance within the autonomic nervous system [12].

2.3.3 Testosterone

Measurement method: Total serum testosterone concentration was measured. Sampling procedures: Venous blood samples (5 mL) were drawn from the antecubital vein. Timing was standardized in the morning (8:00–9:00 a.m.), when testosterone reaches its morning peak. The sample was allowed to clot for 20 minutes, centrifuged at 3000 rpm for 10 minutes, and the serum was stored at −20°C until analysis. Analysis method for Testosterone was analyzed using Chemiluminescence Immunoassay (CLIA) and the unit of measurement was nmol/L [13].

2.3.4 Cortisol

Measurement method: Serum cortisol concentration was measured using the same sample drawn for testosterone analysis.

Measurement procedures: Morning venous blood was drawn, serum was separated by centrifugation, and the analysis was performed using: Chemiluminescent immunoassay. Unit of measurement: nmol/L.

The testosterone-to-cortisol ratio (T/C ratio) was also calculated by dividing testosterone concentration (nmol/L) by cortisol concentration (nmol/L) after standardizing the units to ensure accurate comparison. The ratio was used as an indicator of anabolic–catabolic balance [14].

2.4 High-Load Weightlifting Effort Protocol

The snatch and clean and jerk lifts were performed using 3–5 sets with a limited number of repetitions (1–3 repetitions per set), in accordance with the demands of high-intensity competitive performance in Olympic weightlifting. The intensity was determined on the basis of each participant's previously measured one-repetition maximum (1RM).

The study sample underwent a single training unit of high-load effort designed according to the scientific principles of strength and power training specific to Olympic weightlifting and in line with the requirements of the snatch and clean and jerk lifts.

The protocol included the following:

To optimize training specificity, the protocol involves performing the snatch and clean and jerk at a high intensity of 85–90% of one-repetition maximum (1RM), utilizing limited sets and repetitions to mirror the physiological demands of competitive Olympic weightlifting. To ensure adequate neuromuscular recovery between these high-load efforts, standardized rest intervals of 2–3 minutes are implemented across all sessions. Furthermore, all performance conditions including timing, warm-up routines, exercise sequence, and the training environment are strictly standardized for every participant to maintain the integrity and consistency of the data.

The session was carried out under the direct supervision of the researcher to ensure full adherence to the effort protocol and achievement of the required intensity.

3.5 Statistical analysis

SPSS was used to process the data and results. Correlation coefficients were calculated using Pearson's r. The displayed values represent relative change from baseline. Negative values indicate an inverse relationship between the two variables, whereas positive values indicate a direct relationship. The level of statistical significance was set at 0.05.

3- RESULTS AND DISCUSSION

The results of Table (2) showed significant temporal changes in heart rate variability indicators following high-load weightlifting effort, represented by a sharp decline in RMSSD and a clear increase in LF/HF immediately after effort, followed by gradual recovery within 30 minutes and near-complete restoration after 24 hours. These findings reflect an acute autonomic response characterized by sympathetic dominance and parasympathetic withdrawal as a direct reaction to the physiological stress generated by high-intensity anaerobic performance.

Table (2): Dynamics of heart rate variability (HRV) indicators across different time points

Measurement time	RMSSD (ms) Mean	RMSSD Standard deviation	Significance level	LF/HF Mean	Standard deviation	Significance level
Pre-exercise	52.4	7.8	—	1.42	0.31	—
Immediately post-exercise	28.6	6.1	0.001	3.21	0.55	0.002
30 min post-exercise	39.8	6.9	0.012	2.12	0.44	0.018
24 h post-exercise	49.7	7.3	0.284	1.58	0.29	0.331

Significant at the error level ≤ 0.05

The substantial reduction in RMSSD immediately after effort represents clear evidence of vagal withdrawal, which is considered an expected physiological response following high-load resistance efforts that require maximal neuromuscular recruitment. Recent literature has indicated that reduced RMSSD after high-intensity exercise is associated with increased catecholamine secretion and elevated metabolic stress, leading to a rapid shift toward sympathetic dominance [7]. A recent review also showed that maximal-strength exercise produces an immediate reduction in time-domain HRV indices due to increased demands on central neural control and greater sympathetic activation [16]. The simultaneous rise in LF/HF immediately after effort supports this interpretation, as it indicates a temporary disturbance in autonomic balance in favor of sympathetic activity. Although there is scientific debate regarding the accuracy of LF/HF as an explicit indicator of sympathetic–parasympathetic balance, recent studies still employ it as a complementary marker for understanding the dynamics of autonomic response after acute stress [17]. In the context of weightlifting, recent research has shown that elevated LF/HF after heavy resistance sessions reflects increased central neural arousal associated with the demands of maximal force production [18]. Although LF/HF was used here as an indicator of sympathetic dominance, its interpretation should be approached with caution because of the debate surrounding its precise physiological meaning; therefore, it was supported by RMSSD to strengthen inference. The partial improvement in RMSSD after 30 minutes, accompanied by a relative decrease in LF/HF, indicates the beginning of autonomic rebalance. However, the persistence of significant differences compared with baseline values indicates that autonomic recovery had not yet been completed within the first half hour. This is consistent with Buchheit [19], who indicated that vagal recovery after high-intensity exercise is relatively delayed compared with aerobic exercise, especially when the effort depends on the phosphagen energy system and anaerobic glycolysis.

After 24 hours, RMSSD and LF/HF values returned to levels close to the pre-exercise state with no significant differences, indicating completion of autonomic recovery within a 24-hour time frame in this sample of trained weightlifters. This full recovery reflects the high level of neural adaptation resulting from long-term training in Olympic weightlifting, as athletes possess greater efficiency in restoring autonomic balance after maximal stress [20]. A recent study in strength sports also supports that experienced athlete show faster reactivation of parasympathetic activity than untrained individuals, which is considered an indicator of advanced functional adaptation of the autonomic nervous system [21].

The results of Table (3) showed clear temporal changes in the hormonal response following high-load weightlifting effort, represented by a significant increase in cortisol concentration immediately after effort and its continued elevation after 30 minutes, with a return toward baseline values after 24 hours. In contrast, testosterone did not show significant changes across the different time points. This pattern reflects a differential response between the catabolic axis (HPA axis) and the anabolic–reproductive axis (HPG axis) in the context of high-intensity anaerobic effort.

Table (3): Temporal changes in testosterone and cortisol concentrations (unit of measurement: nmol/L)

Measurement time	Testosterone Mean	Standard deviation	Significance level	Cortisol Mean	Standard deviation	Significance level
Pre-exercise	18.6	2.9	—	412	58	—
Immediately post-exercise	17.9	2.7	0.214	558	72	0.001
30 min post-exercise	18.2	2.8	0.436	496	65	0.009
24 h post-exercise	18.8	3.0	0.612	431	60	0.287

Significant at the error level ≤ 0.05

The acute rise in cortisol immediately after effort (558 nmol/L versus 412 nmol/L at baseline) indicates strong activation of the hypothalamic–pituitary–adrenal (HPA) axis, which is an expected physiological response to high physical stress requiring rapid metabolic mobilization to maintain energy balance. Recent literature indicates that high-load resistance exercise, especially when performed at intensities above 85% of 1RM, increases cortisol secretion because of elevated mechanical and metabolic stress and disruption of homeostasis [22]. Many studies with analytical review also indicated that the cortisol response is more pronounced in protocols combining high intensity with moderate volume, which is consistent with the nature of the present study protocol [14]. This elevation can be explained by the increased need for glucose mobilization, stimulation of muscle protein breakdown, and enhancement of short-term adaptations associated with acute stress. The continued significant elevation after 30 minutes (496 nmol/L) indicates that hormonal recovery is relatively delayed compared with some neural indicators, supporting the idea that restoration of HPA-axis balance requires more time than restoration of vagal autonomic balance. A recent study in strength athletes showed that cortisol may remain elevated for 60–90 minutes after a heavy resistance session, especially in athletes performing Olympic lifts [23].

The return to non-significant values after 24 hours indicates that the applied effort, despite its high intensity, did not produce long-term cumulative stress, but rather remained within the physiological tolerance limits of the trained athletes. This reflects the efficiency of HPA-axis regulation in weightlifters with extended training experience, as recent studies have shown that trained athletes demonstrate an acute yet rapidly resolving cortisol response compared with untrained individuals [24].

Unlike cortisol, testosterone levels did not show significant changes across the different time points despite a slight decrease immediately after effort. This result is consistent with contemporary trends indicating that acute changes in testosterone after a single resistance session may be limited or non-significant in highly trained athletes, especially when the endocrine system has adapted as a result of years of training [25, 26]. The literature indicates that testosterone response depends greatly on total load volume, number of repetitions, and duration of the training session. Whereas high-volume protocols are associated with sharp increases in testosterone, short sessions of high intensity may not produce a noticeable change and may even show stability or a slight decrease because of temporary suppression of the HPG axis under stress [22]. A recent study also clarified that advanced athletes may show a relative hormonal blunting in acute testosterone responses as a result of chronic adaptation, such that the response becomes less variable and more stable compared with beginners [27]. This finding is consistent with the modern physiological model according to which the hormonal response to severe effort passes through two phases: a short-term catabolic energy-mobilization phase followed by an anabolic rebalancing phase during recovery [14]. The return of values to baseline after 24 hours confirms that the effort used did not exceed the athletes' adaptive threshold, but remained within the calculated physiological loading range.

Table (4) showed the physiological significance of the reduction in T/C immediately after effort. The T/C ratio is an integrative indicator of the balance between anabolic and catabolic processes, as it reflects the dynamic relationship between the HPG and HPA axes. The acute reduction after effort in this study was not due to a substantial drop in testosterone, but was driven mainly by the pronounced increase in cortisol, indicating dominance of the acute stress response.

Table (4): Dynamics of the testosterone-to-cortisol ratio (T/C Ratio)

Measurement time	**T/C Ratio Mean**	**Standard deviation**	**Significance level**
Pre-exercise	0.045	0.008	—
Immediately post-exercise	0.032	0.007	0.002
30 min post-exercise	0.037	0.008	0.018
24 h post-exercise	0.044	0.009	0.391

Significant at the error level ≤ 0.05

Previous literature supports this interpretation, as Kraemer et al. [22] explained that the temporary reduction in T/C after high-intensity resistance sessions represents a normal response reflecting immediate energy mobilization rather than an indicator of overtraining. Hackney and Lane (2024) also pointed out that the T/C ratio is more sensitive to acute changes than either hormone alone because it reflects the body's net metabolic direction. Other studies showed that the duration for which T/C remains reduced is related more to load intensity and density than to total volume [23]. In trained strength athletes, the reduction may persist for 30–60 minutes without carrying pathological significance; rather, it is considered part of the series of acute adaptations that precede muscular rebuilding processes. The return of T/C after 24 hours serves as an indicator of adaptive efficiency. The absence of significant differences after 24 hours indicates completion of hormonal recovery within the normal time frame for trained athletes. This finding is consistent with the concept of hormonal resilience, which refers to the ability of a high-level athlete to generate a large response and then return rapidly to baseline without long-term disturbance [24]. Current evidence indicates that a chronic reduction in T/C across several days is what is associated with overtraining or excessive cumulative load, whereas the acute transient reduction observed in this study reflects a normal adaptive response [25].

As shown in Table (5), the results revealed a significant inverse correlation between the change in RMSSD and the change in cortisol after effort, indicating that the greater the reduction in parasympathetic activity (lower RMSSD), the greater the rise in cortisol secretion.

Table (5): Correlation between changes in heart rate variability indicators and hormonal markers after effort

Variables	Correlation coefficient	Significance level
RMSSD × cortisol (immediately post-exercise)	-0.64	0.006
RMSSD × T/C ratio (immediately post-exercise)	0.58	0.014
LF/HF × cortisol (immediately post-exercise)	0.61	0.009
LF/HF × T/C ratio (immediately post-exercise)	-0.55	0.021
RMSSD × cortisol (after 30 minutes)	-0.49	0.047
LF/HF × cortisol (after 30 minutes)	0.52	0.032

Significant at the error level ≤ 0.05

This finding is of considerable physiological importance because it reflects functional integration between the autonomic nervous system and the hypothalamic–pituitary–adrenal (HPA) axis. A reduction in RMSSD represents inhibition of vagal activity and increased sympathetic dominance; a pattern associated with activation of the stress axis and increased cortisol secretion [7]. One of the findings indicates that acute sympathetic activation during high-intensity resistance effort is directly associated with catecholamine release, which in turn stimulates the subsequent cortisol response through activation of the HPA axis [14]. Therefore, the inverse relationship observed in the present results confirms that autonomic disturbance is not an isolated phenomenon, but is functionally linked to the catabolic hormonal response. From an applied perspective, this finding means that a reduction in RMSSD may be used as an early indicator of elevated catabolic hormonal stress after high-load sessions [28].

Regarding the relationship between LF/HF and cortisol, the results showed a significant positive correlation between increased LF/HF and increased cortisol, reflecting that sympathetic dominance is directly associated with a stronger hormonal stress response. Physiologically, this finding can be explained by the fact that LF/HF is considered an indicator of relative sympathetic dominance, and its increase after effort reflects autonomic imbalance in favor of sympathetic activity. Recent studies indicate that the sharp rise in LF/HF after effort is associated with greater activation of the central sympathetic nervous system, which occurs simultaneously with stimulation of ACTH secretion and subsequently cortisol [29]. Previous review in training physiology confirms that elevated LF/HF responses after severe resistance effort are associated with increased markers of hormonal and inflammatory stress [30].

Regarding the relationship between RMSSD and T/C ratio, the results showed a positive correlation between the change in RMSSD and the change in T/C ratio, meaning that restoration of parasympathetic activity is associated with improvement in anabolic–catabolic balance. This relationship is highly important because it indicates that autonomic recovery parallels anabolic hormonal recovery. A reduced T/C ratio reflects a temporary catabolic environment, and when RMSSD begins to improve, the T/C ratio also begins to return toward baseline. Previous research indicates that the balance between the parasympathetic nervous system and the anabolic hormonal environment is a central indicator of performance readiness. Athletes with faster autonomic recovery also demonstrate faster restoration of T/C after high-load effort [23].

Regarding the relationship between LF/HF and testosterone, the correlation results showed no strong significant relationship between the change in LF/HF ratio and the change in testosterone concentration following high-load effort. This finding has important interpretive value because it reflects the difference in the physiological regulation of rapid autonomic response and anabolic androgenic response. Physiologically, increased LF/HF reflects acute sympathetic dominance associated with activation of the sympathetic nervous system and constitutes an immediate and direct response to physical stress. Testosterone, although it is a key anabolic hormone in strength sports, does not respond to acute resistance effort with the same speed or sensitivity as cortisol [31].

4- CONCLUSION

Based on the study, high-load weightlifting triggers an immediate neurohormonal stress response characterized by acute sympathetic dominance and the activation of the hypothalamic-pituitary-adrenal (HPA) axis. This response is marked by a significant reduction in parasympathetic activity (RMSSD) and a sharp increase in cortisol, creating a transient catabolic state that reduces the testosterone-to-cortisol (T/C) ratio. While the autonomic nervous system reacts more rapidly than hormonal markers, the integrated relationship between the two suggests that heart rate variability can serve as an early indicator of catabolic stress. In trained athletes, these physiological shifts are adaptive rather than indicative of excessive fatigue, as both neural and hormonal markers return to baseline within 24 hours. This complete recovery within a day confirms that the training load was within the athletes' optimal adaptive capacity. Ultimately, monitoring the synchronized dynamics of heart rate variability and hormonal balance provides a valuable tool for optimizing training loads and recovery in elite strength sports.

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