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Hormonal adaptations in Indian athletes of different energy system-dominant sports

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Abstract
Hormonal adaptations play a crucial role in athletes' physiological responses to training, recovery, and performance. Testosterone, an anabolic hormone, promotes protein synthesis and muscle development, whereas cortisol, a catabolic hormone, is associated with stress and protein degradation. The Testosterone/Cortisol (T/C) ratio is a recognized marker of anabolic-catabolic balance and a sensitive indicator of overtraining risk. The present study aimed to assess the hormonal profile of athletes engaged in aerobic, anaerobic, and mixed energy system sports to examine sport-specific endocrine adaptations and potential susceptibility to overtraining.

A total of 690 athletes were included in the study, comprising 361 male and 286 female athletes for the reference interval assessment and 246 male and 183 female athletes for evaluation of biochemical changes. Hormonal analysis was conducted for testosterone, cortisol, and the T/C ratio. Statistical analysis included descriptive statistics and ANOVA to determine differences among athletes from aerobic, anaerobic, and aerobic: Anaerobic sports.

Results indicated that testosterone levels were significantly higher in anaerobic athletes compared to aerobic and mixed-energy system athletes in both genders. Cortisol levels were elevated in aerobic athletes, reflecting the catabolic impact of prolonged endurance training. Consequently, the T/C ratio was highest in anaerobic athletes and lowest in aerobic athletes, indicating a favorable anabolic environment in anaerobic sports and increased overtraining risk in endurance sports. The prevalence of abnormal hormonal values, particularly reduced T/C ratios, was greater among aerobic athletes, suggesting a higher susceptibility to training-induced stress and maladaptation.

These findings highlight the influence of energy system dominance on hormonal adaptation and underscore the importance of regular endocrine monitoring in athletes. The assessment of testosterone, cortisol, and T/C ratio provides critical insights into training status, recovery efficiency, and overtraining risk. Integrating hormonal profiling into training programs can facilitate individualized load management, optimize performance, and minimize the risk of long-term physiological disturbances.

Keywords: Testosterone, cortisol, overtraining, energy systems, aerobic athletes, anaerobic athletes

Introduction
The hormonal profile of an athlete is a critical indicator of physiological adaptation to training and recovery [1]. Among the key hormones, testosterone is anabolic, promoting protein synthesis and muscle growth, while cortisol is catabolic and associated with stress and protein degradation [2]. The testosterone/cortisol (T/C) ratio is considered a reliable biomarker of anabolic-catabolic balance and an indicator of overtraining syndrome [3-5]. The balance between these hormones differs with the predominant energy system utilized in training [6]. Aerobic sports such as long-distance running and cycling primarily rely on oxidative metabolism, which may suppress testosterone and increase cortisol secretion due to sustained training stress [7, 8].

In contrast, anaerobic or mixed energy system sports such as sprinting and hockey promote an anabolic state through resistance and high-intensity training stimuli [9, 10].

Overtraining, characterized by hormonal and performance disturbances, remains a major concern for athletes and coaches [11]. Monitoring hormonal changes provides insight into adaptation and recovery efficiency [5, 12]. The present study aimed to assess the hormonal profile (testosterone, cortisol, and T/C ratio) in athletes engaged in aerobic, anaerobic, and aerobic: Anaerobic sports, to identify sport-specific hormonal adaptations and potential overtraining risk [1, 3, 13].

Hormonal fluctuations are influenced not only by the type and intensity of exercise but also by factors such as nutrition, sleep, psychological stress, and training load periodization [14, 15]. Regular evaluation of endocrine markers can therefore serve as a valuable tool for optimizing training programs and preventing maladaptation [11, 16]. Previous studies have shown that endurance athletes tend to exhibit reduced serum testosterone and elevated cortisol levels during heavy training blocks, suggesting chronic stress exposure [7, 17]. Conversely, athletes involved in strength or power-oriented sports often display higher anabolic responses, reflecting improved recovery and muscle remodeling [9, 18].

Furthermore, the T/C ratio has been proposed as a sensitive marker to detect early signs of overtraining before observable declines in performance occur [3, 4, 19]. Understanding these hormonal dynamics across different sporting disciplines provides a scientific foundation for individualized monitoring strategies [12]. Such insights are crucial for sports scientists, coaches, and medical professionals in maintaining the athlete's physiological and psychological well-being [11, 14]. Hence, this study aims to compare and analyze the hormonal variations among athletes representing diverse energy system demands to delineate their adaptive responses and identify potential risks of training-induced hormonal imbalance [13, 16, 19].

Materials and Methods

Study Design and Participants

The study was conducted in two phases

- **Reference interval establishment:** Conducted on 647 healthy athletes (361 males, 286 females) with serum ferritin levels ≥ 12 ng/ml.
- **Hormonal evaluation:** Conducted on 429 athletes (246 males, 183 females) representing aerobic, anaerobic, and aerobic: anaerobic sports. Athletes with injury, illness, or ferritin < 12 ng/ml were excluded.

Energy System Classification

The classification of sports based on dominant energy system was made according to Fox, Bowers, and Foss (1993), Wayne Smith (2006), Abernethy *et al*. (2013) and Salo and Riewald (2008).

Sample Collection and Hormonal Analysis

Venous blood samples were collected between 08:00 and 09:00 AM after overnight fasting and 24-hour rest from exercise. Serum testosterone and cortisol levels were analyzed using immunoassay techniques. The testosterone/ cortisol ratio was calculated for each subject.

Statistical Analysis

Descriptive statistics were expressed as mean ± SD. One-way ANOVA followed by post-hoc LSD tests was applied to determine group differences. A p-value < 0.05 was considered statistically significant. Statistical analyses were performed using SPSS version 9.0 (IBM Corp., USA).

Results

Table 1: Energy system contribution of different sports [20-23]

Game	Energy system	
	Aerobic (%)	Anaerobic (%)
Cycling	80	20
Long Distance Running	90	10
Middle Long Distance Running	80	20
Rowing	80	20
Sprint	20	80
Swimming	80	20
Walker	98	2
Waterpolo	60	40
Hockey	50	50
Wushu	50	50

Table 2: Hormone profile in male athletes of three different games

Parameter	Reference Interval Aerobic	Aerobic, Mean ± SD	Reference Interval Anaerobic	Anaerobic, Mean ± SD	Reference Interval Aerobic: Anaerobic	Aerobic: Anaerobic, Mean ± SD
Testosterone (ng/ml)	1.25-17.1	5.91±4.31	2.15-15.41	8.38±4.10	1.53-13.96	6.54±4.20
Cortisol (ng/ml)	50.31-632.6	215.5±178.9	49.56-425.87	181.8±179.5	44.69-561.7	197.7±153.6
Testosterone/cortisol Ratio	0.0077-0.1638	0.0471±0.05	0.0089-0.1965	0.0831±0.06	0.0053-0.1570	0.0547±0.05

Table 3: Hormone profile in female athletes of three different games

Parameter	Reference Interval Aerobic	Aerobic, Mean ± SD	Reference Interval Anaerobic	Anaerobic, Mean ± SD	Reference Interval Aerobic: Anaerobic	Aerobic: Anaerobic, Mean ± SD
Testosterone (ng/ml)	0.0034-1.889	0.449±0.62	0.383-1.424	0.913±0.68	0.009-1.87	0.619±0.55
Cortisol (ng/ml)	34.66-604.51	174.8±116.4	24.71-157.78	87.22±24.28	59-494.9	136.6±113.5
Testosterone/cortisol Ratio	0.0003-0.0339	0.0035±0.006	0.0019-0.0372	0.0121±0.012	0.0004-0.1606	0.0063±0.007

Table 4: ANOVA test of hormone profile in male athletes

Parameter		Sum of squares	DF	Mean square	F	Significant	Post-hoc test (LSD)	Significant
Testosterone (ng/ml)	Between groups Within groups Total	130.61 4383.86 4514.47	2 243 245	65.31 18.04	3.620	0.028	I vs II II vs III	0.008 0.050
Cortisol (ng/ml)	Between groups Within groups Total	32555.04 7025653 7058208	2 243 245	16277.52 28912.15	0.563	0.570	NS	NS
Testosterone/cortisol ratio	Between groups Within groups Total	0.027 0.675 0.702	2 243 245	0.014 0.003	4.941	0.008	I vs II II vs III	0.002 0.017

Table 5: ANOVA test of hormone profile in female athletes

Parameter		Sum of squares	DF	Mean square	F	Significant	Post-hoc test(LSD)	Significant
Testosterone (ng/ml)	Between groups Within groups Total	2.393 61.20 63.59	2 180 182	1.197 0.340	3.519	0.032	I vs II	0.020
Cortisol (ng/ml)	Between groups Within groups Total	98238.36 2249602 2347840	2 180 182	49119.18 12497.79	3.930	0.021	I vs II I vs III	0.022 0.030
Testosterone/cortisol ratio	Between groups Within groups Total	0.001 0.008 0.009	2 180 182	0.000 0.000	8.339	0.000	I vs II I vs III II vs III	0.000 0.009 0.010

Table 6: Percentage of population of male athletes having abnormal hormones values

Parameter	Aerobic	Anaerobic	Aerobic: Anaerobic
Testosterone (ng/ml)	13.1%	12%	12.1%
Cortisol (ng/ml)	10%	8%	8.8%
Testosterone/cortisol ratio	16.9%	12%	8.8%

Table 7: Percentage of population of female athletes having abnormal hormones values

Parameter	Aerobic	Anaerobic	Aerobic: Anaerobic
Testosterone (ng/ml)	6.2%	0%	5.6%
Cortisol (ng/ml)	3.0%	0%	2.8%
Testosterone/cortisol ratio	13.6%	0%	6.5%

Hormone profile of male and female athletes in three different games
I-Aerobic, II-Anaerobic, III-Aerobic: Anaerobic

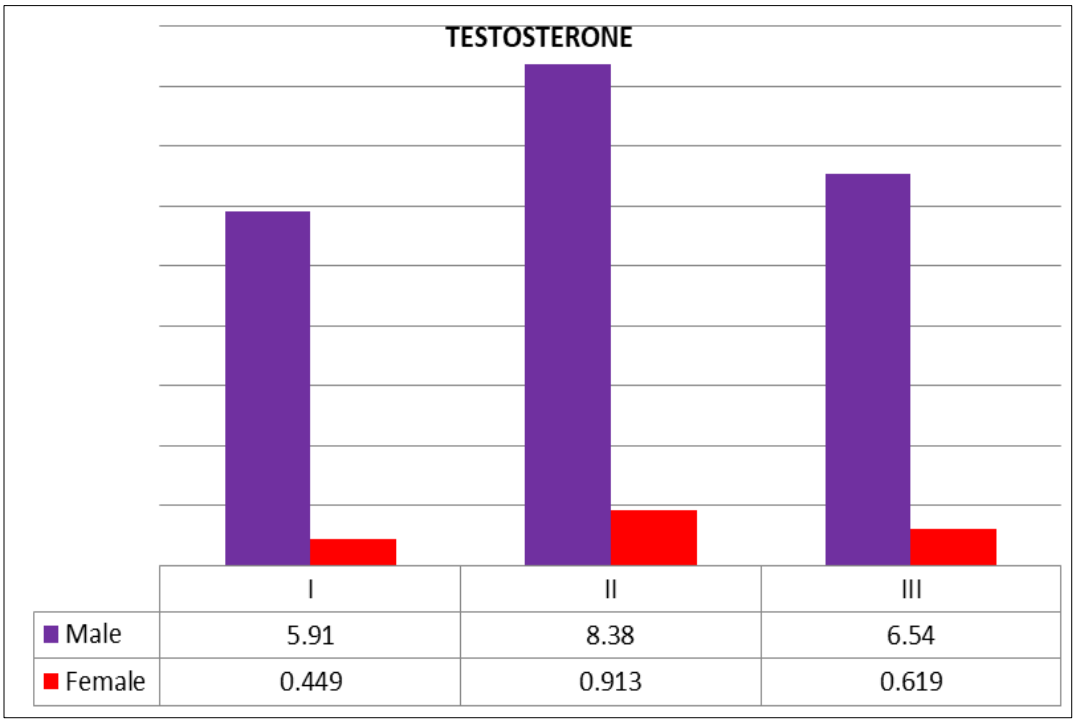
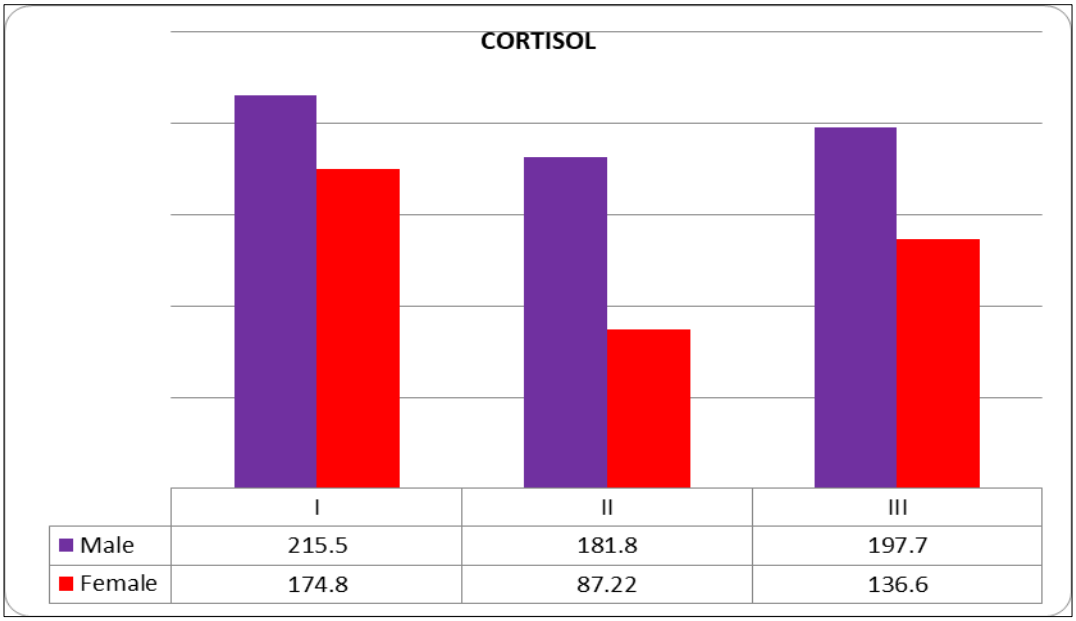
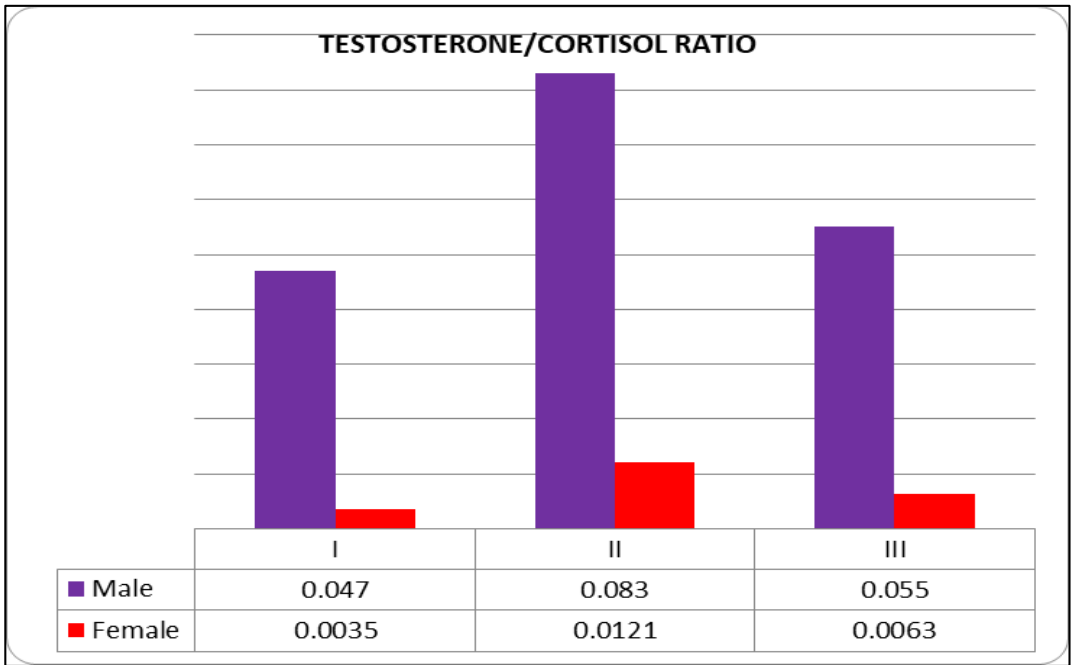


Fig 1: Testosterone level of male & female athletes in three different games



	I	II	III
Male	215.5	181.8	197.7
Female	174.8	87.22	136.6

Fig 2: Cortisol level of male & female athletes in three different games



	I	II	III
Male	0.047	0.083	0.055
Female	0.0035	0.0121	0.0063

Fig 3: T/C ratio level of male & female athletes in three different games

Discussion

The present study evaluated the hormonal profile of male and female athletes representing aerobic, anaerobic, and aerobic: Anaerobic sports to explore sport-specific endocrine adaptations and potential indicators of overtraining. The analysis of testosterone, cortisol, and the testosterone/cortisol (T/C) ratio revealed distinct hormonal patterns associated with the predominant energy system demands of each sport.

In male athletes, testosterone levels were significantly higher in the anaerobic group compared to the aerobic and aerobic: Anaerobic groups. This observation aligns with previous findings suggesting that high-intensity and resistance-based activities stimulate anabolic hormonal responses through enhanced activation of the hypothalamic-pituitary-gonadal (HPG) axis [24, 25]. Testosterone is known to facilitate protein synthesis, muscle repair, and erythropoiesis key factors contributing to performance enhancement in strength and power sports [26]. In contrast, endurance training characterized by prolonged oxidative metabolism has been shown to suppress testosterone secretion, likely due to increased metabolic stress, reduced energy availability, and inhibition of gonadotropin-releasing hormone (GnRH) pulsatility [27, 28].

Although the cortisol levels did not differ significantly between male athlete groups, the aerobic athletes exhibited a trend toward elevated mean cortisol levels compared to anaerobic counterparts. Cortisol is a catabolic hormone secreted in response to physiological and psychological stress, promoting protein degradation and gluconeogenesis to maintain energy homeostasis [29]. Sustained elevation of cortisol has been associated with chronic training stress and impaired recovery [30]. The lack of significant variation in cortisol levels in this study could be attributed to individual differences in training load, nutrition, and circadian rhythm, all of which influence cortisol secretion [31].

The testosterone/cortisol ratio is widely recognized as a sensitive indicator of the anabolic-catabolic balance and a marker of overtraining [32]. A higher T/C ratio reflects an anabolic state conducive to muscle adaptation and recovery, whereas a decline indicates catabolic dominance and potential fatigue. In the present study, anaerobic male athletes displayed a significantly higher T/C ratio than aerobic athletes, suggesting better recovery status and favorable adaptation. These findings corroborate with Kraemer and Ratamess [33], who demonstrated that short-duration, high-intensity training enhances anabolic hormone responses, while prolonged endurance training reduces this balance.

Among female athletes, a similar pattern was observed: testosterone and the T/C ratio were significantly higher in anaerobic athletes compared to aerobic athletes. These results mirror prior studies indicating that female athletes engaging in high-intensity training exhibit more pronounced anabolic responses than those involved in endurance sports [34, 35]. Elevated cortisol levels among aerobic female athletes may reflect cumulative training stress and insufficient recovery intervals, as previously reported in long-distance runners and swimmers [36]. Notably, despite lower absolute testosterone levels in females, the relative changes in the T/C ratio can effectively indicate physiological strain, as suggested by Viru and Viru [37].

The prevalence of abnormal hormonal values reinforces these findings. Approximately 16.9% of male and 13.6% of female aerobic athletes demonstrated T/C ratios outside the reference range, indicating a higher likelihood of hormonal imbalance and overtraining risk. Urhausen and Kindermann [38] emphasized that a persistent reduction (>30%) in the T/C ratio over time is a reliable early marker of overtraining syndrome, even before measurable declines in performance occur. Such endocrine monitoring can thus serve as a valuable non-invasive tool for athlete management and training load adjustment.

The observed sport-specific hormonal adaptations can be attributed to differences in exercise intensity, duration, and energy system utilization. Aerobic sports predominantly engage oxidative metabolism, leading to prolonged cortisol activation, while anaerobic or mixed-energy sports stimulate greater testosterone release due to intermittent high-intensity muscle contractions [39, 40]. These findings are consistent with the model proposed by Hackney [41], who reported that endurance training induces a chronic suppression of the hypothalamic-pituitary-gonadal axis, whereas resistance training enhances testosterone output and supports an anabolic environment.

From a practical perspective, the current results underscore the need for individualized monitoring of hormonal responses in athletes. Regular assessment of testosterone, cortisol, and the T/C ratio can help coaches and sports scientists identify early signs of overtraining, optimize training periodization, and ensure adequate recovery. Furthermore, integrating biochemical monitoring with subjective and performance-based indicators such as heart rate variability, perceived exertion, and sleep quality could provide a comprehensive framework for athlete health management [42].

Conclusion

The present study demonstrated distinct hormonal adaptations among athletes based on the predominant energy system utilized in their sport. Anaerobic athletes exhibited significantly higher testosterone levels and a favorable testosterone/cortisol (T/C) ratio, reflecting a strong anabolic environment and effective recovery status. In contrast, aerobic athletes showed comparatively lower testosterone and T/C ratios, indicative of greater physiological stress and potential catabolic dominance. Female athletes displayed similar trends, though with lower absolute hormone concentrations due to gender-related physiological differences.

The higher incidence of abnormal T/C ratios among aerobic athletes highlights the increased susceptibility of endurance performers to overtraining and hormonal imbalance. Regular endocrine monitoring of testosterone, cortisol, and the T/C ratio provides a valuable tool for early detection of overtraining, optimization of training load, and ensuring adequate recovery.

Overall, this study emphasizes the importance of sport-specific hormonal profiling as an evidence-based approach to athlete management. Integrating biochemical monitoring with training periodization, nutrition, and psychological recovery strategies can enhance performance outcomes while minimizing the risk of overtraining and long-term physiological disruption.

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