Journal of Strength and Conditioning Research, 2007, 21(4), 1146–1154

The Acute Effects of Twenty-Four Hours of Sleep Loss on the Performance of National-Caliber Male Collegiate Weightlifters

Peter A. Blumert,[1] Aaron J. Crum,[1] Mark Ernsting,[1,4] Jeff S. Volek,[2] Daniel B. Hollander,[3] Erin E. Haff,[1,6] and G. Gregory Haff[1,5]

[1]Exercise Physiology Laboratory, Midwestern State University, Wichita Falls, Texas 76308; [2]Human Performance Laboratory, Department of Kinesiology, University of Connecticut, Storrs, Connecticut 06269; [3]Department of Kinesiology and Health Studies, Southeastern Louisiana University, Hammond, Louisiana 70402; [4]Department of Exercise Science, West Virginia Wesleyan College, Buckhannon, West Virginia 26201; [5]Division of Exercise Science, Department of Human Performance, West Virginia School of Medicine, Morgantown, West Virginia 26506; [6]Eberly College of Arts and Sciences, West Virginia University, Morgantown, West Virginia 26506.

Abstract. Blumert, P.A., A.J. Crum, M. Ernsting, J.S. Volek, D.B. Hollander, E.E. Haff, and G.G. Haff. The acute effects of twenty-four hours of sleep loss on the performance of national-caliber male collegiate weightlifters. *J. Strength Cond. Res. 21(4):1146–1154. 2007.*—Currently, the degree to which sleep loss influences weightlifting performance is unknown. This study compared the effects of 24 hours of sleep loss on weightlifting performance and subjective ratings of psychological states pre-exercise and postexercise in national-caliber male collegiate weightlifters. Nine males performed a maximal weightlifting protocol following 24 hours of sleep loss and a night of normal sleep. The subjects participated in a randomized, counterbalanced design with each sleep condition separated by 7 days. Testosterone and cortisol levels were quantified prior to, immediately after, and 1 hour after the resistance training session. Additionally, profile of mood states and subjective sleepiness were evaluated at the same time points. The resistance training protocol consisted of several sets of snatches, clean and jerks, and front squats. Performance was evaluated as individual exercise volume load, training intensity and overall workout volume load, and training intensity. During each training session the maximum weight lifted for the snatch, clean and jerk, and front squat were noted. No significant differences were found for any of the performance variables. A significant decrease following the sleep condition was noted for cortisol concentration immediately after and 1 hour postexercise. Vigor, fatigue, confusion, total mood disturbance, and sleepiness were all significantly altered by sleep loss. These data suggest that 24 hours of sleep loss has no adverse effects on weightlifting performance. If an athlete is in an acute period of sleep loss, as noticed by negative mood disturbances, it may be more beneficial to focus on the psychological (motivation) rather than the physiological aspect of the sport.

Key Words. sleep deprivation, weightlifting, hormones, profile of mood states

Introduction

Sleep deprivation has been described as a state of being in which adequate sleep has not been received (60). The scientific literature suggests that sleep and recovery play a very large role in how the athlete adapts to training and ultimately performs (46, 49, 58). Athletes who are sleep-deprived have been reported to experience a decrease in competitive performance and have reduced levels of determination or intensity in training (3, 45, 48). Sleep deprivation may also cause mood changes, greater levels of fatigue, depression, and confusion (4, 40, 62). The deterioration of mood can have a tremendous effect on motivation, which is important for athletes participating in training and competition (3, 45).

Generally, it has been reported that college students are among the most sleep-deprived people in the nation (17), and collegiate athletes report an even greater loss of sleep than traditional college students (42). Several different scenarios might be postulated in which a collegiate athlete, such as a weightlifter, might experience an acute period of sleep loss. These possibilities may include, but are not limited to (a) cramming for exams, (b) travel across several time zones (61), and (c) nervous anticipation prior to a major competition which prevents the athlete from getting enough sleep (42), and stress from cutting weight (Coach G. Pendlay, personal communication, September 2003). These scenarios have the potential to generate an acute period of sleep loss that may theoretically result in decreased performances. It is likely that when this is a frequent occurrence, chronic sleep deprivation may result, which has the potential to decrease either training or competitive performance.

When looking at the effects of acute periods of sleep loss, ranging from 24–60 hours, on anaerobic performance as assessed by the Wingate Anaerobic cycle test, the scientific literature reveals no performance decrements (6, 33, 51, 54). Additionally, when examining grip performance, no significant changes in performance occur in response to partial sleep deprivation (46), 24 hours (11, 32), or 64 hours (55) of sleep loss. Conversely, it appears that a minimum of 30 hours of sleep loss is needed in order for significant performance decrements to be manifested (7, 51, 55). Souissi et al. (51) reported that after 36 hours of sleep loss significant decreases in peak and average power generating capacity occur. Similarly, Bulbulian et al. (7) reported significant decreases in isokinetic performance in response to 30 hours of sleep loss. When examining these studies, it can be clearly seen that most require the athlete to perform one testing bout that last for a limited amount of time. It is possible to hypothesize that modeling an anaerobic training session or an extended anaerobic testing protocol might create a physiological stimuli that is strong enough to result in shorter periods (<30 h) of acute sleep loss creating an overall performance decline.

Additionally, it is possible that the type of task utilized might mitigate the effects of sleep loss on performance. In support of this contention, Takeuchi et al. (55) reported that 64 hours of sleep deprivation resulted in decreased vertical jump performance and isokinetic knee extension strength, while isometric strength and 40-m dash performance were unaffected. Even when looking at partial sleep deprivation over three days, it can be noted that decrements in performance occurred in the more skill-oriented or total body resistance training exercises such as the deadlift, leg press, and bench press, while there were no alterations in the bicep curl performance (47). Based upon this literature, it might be hypothesized that athletes who are performing a more complex task, such as the clean and jerk or snatch, might experience a greater performance decrement in response to an acute period of sleep deprivation.

Acute performance decrements experienced in response to periods of sleep loss or deprivation may be linked to acute alterations in basal levels of cortisol and testosterone (1, 35–37, 44). Testosterone and cortisol have been suggested to be strongly related to strength power performance or athletic preparedness in the scientific literature (14, 16). Thus, it might be speculated that alteration in either of these two hormones during periods of acute sleep loss or deprivation might result in alterations in strength/power performance. Contemporary literature exploring the effects of sleep deprivation on basal levels of cortisol has demonstrated variable results with some studies reporting increases (37, 44), decreases (2), or no change (24, 30, 36) in basal cortisol concentrations. Conversely, it appears that testosterone levels are depressed when sleep deprivation is coupled with physical strain (1, 35, 36). Based upon these studies, it is likely that acute periods of sleep deprivation may result in a suppression of testosterone levels and an elevation of cortisol levels both of which may impact athletic performance.

Probably the most noted effects of acute periods of sleep loss or deprivation (<24 hours) are manifested as decrements in psychological performance variables (41). Meney et al. (32) report that vigor, fatigue, confusion, and total mood disturbances, as assessed by the profile of mood states, were negatively impacted after 24 hours of sleep loss. It has also been reported that mood is more affected by sleep loss or deprivation than either cognitive or motor performance (41). Generally, decrements in mood states occur in advance of physical performance decrements, particularly if there is extrinsic motivation to succeed (38). Overall, the greater the amount of total stress (sleep deprivation, caloric deficit, prolonged work) the greater the changes in psychological measures associated with the profile of mode states. Decreases in mood are generally associated with decreases in motivation, which can significantly impact both training and competitive performance (3, 45).

Interestingly, when looking at the current body of data examining acute bouts of sleep loss, two things are striking: (a) it appears that none of the studies have actually modeled a training session that requires the performance of a series of high-intensity exercises that are performed for multiple sets and repetitions and (b) none of the activities modeled use technical skills similar to those employed in an actual training session or competition. Additionally, to the authors' knowledge, no studies have been completed which look at the acute physiological and psychological affects of sleep loss in high-velocity and high-intensity exercises, such as Olympic-style weightlifting, that are performed with multiple sets and exercises similar to those encountered during a typical training session. Therefore, the primary purpose of this study was to examine the effects of 24 hours of sleep loss on various markers of physiological and psychological performance during a high intensity training session undertaken by national-caliber collegiate male weightlifters.

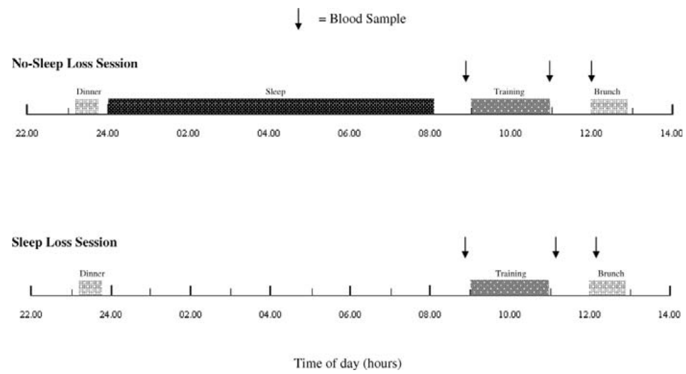

FIGURE 1. Testing timeline.

TABLE 1. Workout protocol.*

Exercise	Repetitions (based on 1RM)
Snatch	2 × 70%, 2 × 80%, 1 × 90%, 1 × 95%, 2–3 × (1 × 100%)
Clean and jerk	2 × 70%, 2 × 80%, 1 × 90%, 1 × 95%, 2–3 × (1 × 100%)
Front squat	2 × 70%, 2 × 80%, 1 × 90%, 1 × 95%, 2–3 × (1 × 100%), 3 × (3 × 85%), 2 × (6 × 70%)

* Modified from Häkkinen et al. (14, 15). 1RM = one repetition maximum.

METHODS

Experimental Approach to the Problem

The present study utilized a randomized counterbalanced design to investigate the effects of 24 hours of sleep loss on various markers of physiological and psychological performance during a typical training session performed by national-caliber collegiate male weightlifters. The subjects were tested on three different occasions. The first testing session was used to determine the subjects' 1 repetition maximum (1RM) in the snatch, clean and jerk, and front squat. The second and third testing sessions were the experimental conditions where the subjects were randomly assigned to various lengths of sleep in a counterbalanced fashion. In the nonsleep loss and sleep loss sessions, the duration of sleep was 8 and 0 hours, respectively. For a summary of the testing timeline, please refer to Figure 1. Following the period of sleep, the subjects performed an intensive weightlifting training session adapted from Häkkinen et al. (13, 15) (Table 1). Each experimental condition was separated by exactly 7 days and was performed at the same time of day.

Subjects

Nine collegiate national-caliber male weightlifters who were in the middle of a strength phase of a periodized training program volunteered to be subjects for the present investigation. Subjects had a minimum of one year of previous training experience with the Olympic-style lifts. All subjects had met the qualifying total for the 2004 USA Weightlifting Collegiate Nationals in their respective weight class by lifting an average total of 120.4 ± 13.7%

Table 2. Subject characteristics (N = 9).*

Variable	Mean ± *SD*
Age (y)	20.7 ± 1.2
Height (cm)	178.6 ± 7.8
Body mass (kg)	102.3 ± 28.1
Body fat (%)	16.7 ± 7.5
1RM snatch (kg)	103.6 ± 14.8
1RM clean and jerk (kg)	123.3 ± 19.5
1RM front squat (kg)	139.4 ± 24.4
Percent 2004 collegiate qualifying total (%)	120.4 ± 13.7

* 1RM = one repetition maximum.

of the total required to lift in the competition. Additionally, all subjects were training on the same collegiate team and utilized an identical training program prior to the initiation of the study. Subjects habitually slept 8 (±1) hours a night as determined by the pretesting sleep log. All subjects were moderately evening to intermediate chronotypes based on the "morningness-eveningness" questionnaire (score between 31 and 58) (21).

Subjects' biometric data are provided in Table 2. Prior to participating in this investigation, all subjects read and signed an informed consent and completed a health history questionnaire in accordance with guidelines set forth by the human subjects review committee at Midwestern State University (HSRC #04061101). All subjects were required to have not been consuming caffeine or other dietary supplements for the 4 weeks prior to the study in order to be considered for participation.

Experimental Protocol

Preliminary Testing. During the first testing session, subjects had their height, body mass, and body composition assessed. Height was measured to the nearest 0.1 cm using a stadiometer, and body mass was determined to the nearest 0.1 kg using an electronic scale. A 7-site skinfold measurement was performed by the same tester in order to assess body composition on all of the subjects. Test-retest reliability has consistently produced high intraclass correlations (ICC = 0.99) for this procedure in our laboratories. Skinfolds were measured using Harpenden Skinfold Calipers (Baty International, England) on the right side of the body three times at each site with the median value recorded (22). The Siri equation was used to estimate percent body fat for each subject (50).

The subjects then performed the snatch, clean and jerk, and front squat with standard methods (15) and maximums were determined via the use of a modified 1RM protocol (52). Briefly, this protocol required subjects to warm-up as if they were preparing for a competition as suggested by the United States Weightlifting Federation (23). After the completion of the warm-up, subjects performed maximal attempts with progressive resistances until there were 2 successive misses. The same warm-up and testing protocol was used for each of the three exercises tested. Thirty minutes of recovery was given between each exercise. The exercises were tested in the following order: snatch, clean and jerk, and front squat. Maximal testing has been highly reliable in our lab as indicated by an ICC >0.98.

Each subject was required to keep a sleep and training journal prior to each of the experimental sessions. The sleep journal required the athletes to record the duration and quality of sleep for the 4 days prior to each experimental session. Training journals were used to record the training volume, intensity, and exercise undertaken during the week prior to each experimental condition. In order to strengthen the training log, data researchers observed and assisted athletes during each week of training. All athletes were on an identical program as determined by the collegiate weightlifting coach. Finally, subjects recorded their dietary intake for the 3 days prior to each experimental day. Prior to participating in each experimental condition, the subjects' pre-experimental condition sleep, activity, and diet compliance were verified by careful examination of the sleep, training journals, and dietary records.

Experimental Treatments. On the day preceding each experimental session, subjects were instructed to refrain from any strenuous activity (training) and to consume the foods they generally eat as indicated in their dietary log.

For the second testing session, subjects were notified the day before at 15:00 hours as to which testing session they were randomly selected to perform. The subjects that were not assigned the experimental treatment slept at home and were instructed to go to sleep at 24:00 and awake at 08:00. The subjects that were assigned the experimental treatment were required to report to the laboratory by 23:30. The subjects were quarantined in the laboratory and monitored by the research staff. All subjects were not allowed to sleep and they stayed awake via watching television, reading, working on a computer, conversation, and playing video and card games. Subjects were strictly supervised by the research staff in order to avoid any eating, napping, or consumption of alcohol or caffeinated beverages. Any subjects who did not follow these strict guidelines were removed from the investigation. The third testing session was identical to the second testing session except that the subjects switched experimental treatments.

Psychological Assessments. For the second and third testing sessions, the subjects reported to the Human Performance Laboratory by 08:30. Prior to exercise, the subjects were instructed to sit in a chair while their subjective sleepiness (18) and profile of mood states (POMS) (31) were recorded. The POMS instrument was administered with the procedures outline by McNair et al. (31). The training session was initiated at 09:00. The subjects performed warm-up lifts with lighter weights before beginning the workout protocol. All subjects were familiarized with the ratings of perceived exertion (RPE) scale during the preliminary testing. A standardized script of instructions was used in the description of the RPE scale every time it was administered in order to insure accuracy in the collection of this data (59). RPE were measured immediately after each maximal set (5). Subjective sleepiness and POMS were obtained directly following the workout.

Hormonal Analyses. When subjects reported to the laboratory, they were required to sit quietly for 15 minutes after which a 10-ml blood sample was collected from an antecubital vein. A 10-ml blood sample was collected immediately after and 1 hour postworkout. Subjects were only allowed to consume water during the workout and during the 1 hour time period after the completion of the training session. Immediately after each blood draw, hematocrit was measured with standard procedures. Hematocrit values were then used to estimate the plasma volume shift (57). The Vacutainer with the remaining blood was then placed in an IEC Centra MP4 centrifuge (Thermo Fisher Scientific, Waltham, MA) with the temperature set at 4° C and spun for 30 minutes at 2,750g. The serum was then separated using disposable plastic

TABLE 3. Pretest performance and dietary variables (N = 9).*

Variable	Sleep loss week Mean ± *SD*	No sleep loss week Mean ± *SD*
Volume load (kg)	8,609.94 ± 5,869.12	8,611.11 ± 5,951.44
Training intensity (kg)	69.70 ± 27.18	70.52 ± 27.85
Hours of sleep (days 3–6)	31.81 ± 4.33	30.61 ± 4.13
kcal	3,016.55 ± 1,174.49	3,019.74 ± 1,185.47
PRO (g)	141.63 ± 49.56	133.74 ± 45.45
Fat (g)	143.51 ± 52.88	134.11 ± 63.01
CHO (g)	298.00 ± 177.44	332.79 ± 169.46

* PRO = protein; CHO = carbohydrate.

TABLE 4. Performance variables (N = 9).*

Variable	Sleep loss Mean ± *SD*	No sleep loss Mean ± *SD*
Snatch 1RM (kg)	97.78 ± 17.43	97.78 ± 17.87
Snatch VL (kg)	823.33 ± 153.45	815.28 ± 157.10
Snatch TI (kg)	53.27 ± 8.07	53.09 ± 9.06
Clean and jerk 1RM (kg)	115.56 ± 16.99	116.67 ± 17.85
Clean and jerk VL (kg)	704.17 ± 147.58	718.06 ± 118.84
Clean and jerk TI (kg)	87.21 ± 16.42	87.70 ± 17.10
Front squat 1RM (kg)	137.50 ± 22.43	134.44 ± 22.18
Front squat VL (kg)	2,505.00 ± 851.70	2,739.44 ± 964.61
Front squat TI (kg)	103.72 ± 19.38	104.49 ± 19.34
Workout VL (kg)	4,032.50 ± 843.05	4,272.78 ± 1,077.87
Workout TI (kg)	82.79 ± 12.97	83.95 ± 14.10

* 1RM = one repetition maximum; VL = volume load; TI = training intensity.

transfer pipettes and placed in labeled microtubes and immediately frozen at −85° C for subsequent analysis of testosterone, cortisol, and the calculation of the testosterone/cortisol (T/C) ratio.

All samples for each hormone were determined in duplicate and were thawed only once for each assay procedure. Plasma testosterone and cortisol were determined using an enzyme immunosorbent assay (EIA) with sensitivities of 0.14 and 2.8 $nmol \cdot L^{-1}$, respectively (Diagnostic Systems Laboratory, Webster, TX). Absorbances were read on a multilabel counter (VersaMax; Molecular Devices, Sunnyvale, CA). Intra-assay variances for testosterone and cortisol were 2.4 and 6.7%, respectively.

Statistical Analyses

Paired comparisons were utilized in the analysis of all dietary data, weightlifting performance data, and the ratings of perceived exertions. A 2 × 3 repeated measures analysis of variance (ANOVA) was used to determine significant differences between the two sleep protocols and the different blood measures. When significant F values were determined ($p \leq 0.05$), paired comparisons were used in conjunction with the Holm's Bonferroni method for controlling type I error (19), to determine the significant differences. A 2 × 2 repeated measures ANOVA was used to determine significant differences between the two sleep protocols for subjective sleepiness and the individual POMS sub categories. Follow-up paired comparisons were utilized in conjunction with a Holm's Bonferroni procedure for controlling type I errors when significant F values were determined ($p \leq 0.05$) (20). All data were reported as mean ± *SD*. Power analyses revealed power values of 0.23–0.98 depending upon which POMS values were analyzed and 0.80 for the statistical procedures associated with the subjective sleepiness scale. When looking at the power values, the statistics associated with the assessment of cortisol powers ranged from 0.05 to 0.95. The statistical analyses associated with testosterone exhibited power values were between 0.06 and 0.56. Statistical significance was set at the $p \leq 0.05$ level of confidence. All analyses were performed via SPSS (version 12.2; SPSS, Inc., Chicago, IL).

RESULTS

There were no significant differences between the training volume ($p = 0.99$, $\eta^2 = 0.002$), training intensity ($p = 0.38$, $\eta^2 = 0.06$), and hours of sleep ($p = 0.17$, $\eta^2 = 0.14$) during the week prior to each testing session. Additionally, no differences were determined between the total kcal ($p = 0.86$, $\eta^2 = 0.004$) consumed and the grams of carbohydrate ($p = 0.11$, $\eta^2 = 0.29$), protein ($p = 0.14$, $\eta^2 = 0.25$), and fat ($p = 0.18$, $\eta^2 = 0.21$) in the days prior to each testing session. Pretesting data are presented in Table 3.

The analysis of the performance data revealed no significant differences between the sleep-deprived condition and the nonsleep-deprived condition for any of the variables measured. A summary of the results of these variables is presented in Tables 4 and 5.

The analysis of the data collected with the use of the POMS revealed a significant difference between the two sleep conditions ($p = 0.002$, $1 - \beta = 0.98$, $\eta^2 = 0.73$) for vigor. Follow-up tests revealed significant differences between the nonsleep-deprived and sleep-deprived conditions for the pre-exercise measurement ($p = 0.009$, $\eta^2 = 0.46$) and the postexercise measurement ($p = 0.004$, $\eta^2 = 0.53$) when assessing vigor. Confusion was also significantly different between the two sleep conditions ($p = 0.003$, $1 - \beta = 0.96$, $\eta^2 = 0.70$) with pre-exercise ($p = 0.008$, $\eta^2 = 0.47$) and postexercise ($p = 0.004$, $\eta^2 = 0.53$) being significantly higher in the sleep-deprived condition. A significant difference was found between the two sleep

TABLE 5. Profile of mood states and subjective sleepiness ($N = 9$).

	Sleep loss		No sleep loss	
	Pre	Post	Pre	Post
Variable	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*
Vigor	15.3 ± 6.1*	12.4 ± 4.0*	19.9 ± 4.9	19.3 ± 6.3
Anger	18.4 ± 8.2	22.0 ± 10.5	13.9 ± 3.4	14.6 ± 4.0
Confusion	13.1 ± 4.0*	13.1 ± 4.7*	10.0 ± 1.7	9.1 ± 2.4
Tension	14.7 ± 4.0	13.4 ± 3.5	12.8 ± 1.9	13.2 ± 3.0
Fatigue	18.4 ± 5.8*†	22.4 ± 5.8*	12.1 ± 3.8†	18.0 ± 6.0‡
Depression	22.0 ± 7.1	22.6 ± 7.3	17.6 ± 4.4	19.7 ± 4.6
Total mood	102.0 ± 20.4‡	106.0 ± 19.0‡	86.2 ± 12.2†	93.9 ± 13.4
Sleepiness	4.0 ± 1.0	4.0 ± 1.6*	3.1 ± 1.2	2.2 ± 1.2

* Significantly different sleep loss to no sleep loss ($p < 0.01$).
† Significantly different pre to post ($p < 0.01$).
‡ Significantly different sleep loss to no sleep loss ($p < 0.05$).

conditions ($p < 0.001$, $1 - \beta = 0.99$, $\eta^2 = 0.82$) and between the pre-exercise and postexercise measures ($p = 0.001$, $1 - \beta = 0.99$, $\eta^2 = 0.75$) when examining the feelings of fatigue. Paired comparison follow-up tests revealed that the postexercise measurement of fatigue was significantly higher in both the nonsleep-deprived ($p = 0.005$, $\eta^2 = 0.65$) and sleep-deprived conditions ($p = 0.03$, $\eta^2 = 0.43$) when compared to the pre-exercise values. Additionally, fatigue was significantly higher in the sleep-deprived condition pre-exercise ($p = 0.007$, $\eta^2 = 0.62$) and postexercise ($p = 0.006$, $\eta^2 = 0.63$) when compared to the nonsleep-deprived condition. A significant difference was noted for depression between conditions ($p = 0.032$, $1 - \beta = 0.62$, $\eta^2 = 0.46$), but not over time ($p = 0.100$, $1 - \beta = 0.37$, $\eta^2 = 0.30$). However, when controlling for type I error, no significant differences were determined between conditions before ($p = 0.069$, $\eta^2 = 0.24$) or after exercise ($p = 0.035$, $\eta^2 = 0.32$). No significant differences were noted for anger ($p = 0.051$, $1 - \beta = 0.52$, $\eta^2 = 0.40$) or for tension ($p = 0.208$, $1 - \beta = 0.23$, $\eta^2 = 0.19$) between the two sleep conditions. When examining the total mood scores as calculated from the POMS, it was determined that a significant difference existed between conditions ($p = 0.01$, $1 - \beta = 0.81$, $\eta^2 = 0.58$) and between pretesting and posttesting measures ($p = 0.05$, $1 - \beta = 0.53$, $\eta^2 = 0.40$). Follow-up tests revealed that the total mood disturbance was significantly higher prior to ($p = 0.03$, $\eta^2 = 0.32$) and immediately after ($p = 0.01$, $\eta^2 = 0.43$) the exercise session on the sleep-deprived day when compared to the nonsleep-deprived condition. No significant differences in mood disturbance were noted between the pre-exercise and postexercise assessment on the sleep-deprived day ($p = 0.44$, $\eta^2 = 0.05$). Conversely, during the nonsleep-deprived condition, a significant ($p = 0.003$, $\eta^2 = 0.56$) increase in total mood disturbance was noted between the pre-exercise and postexercise testing period. Additionally, there was a significant difference in the feelings of sleepiness between the two sleep conditions ($p = 0.013$, $1 - \beta = 0.80$, $\eta^2 = 0.56$), but not over time ($p = 0.24$, $1 - \beta = 0.20$, $\eta^2 = 0.17$). Sleepiness was not significantly different between conditions at the pre-exercise time point ($p = 0.14$, $\eta^2 = 0.25$), but was significantly lower in the nonsleep-deprived condition at the postexercise measurement ($p = 0.007$, $\eta^2 = 0.62$). A summary of the psychological variables assessed can be found in Table 6.

No significant differences were noted between the two sleep conditions for ratings of perceived exertion after the snatch ($p = 0.90$, $\eta^2 = 0.002$), clean and jerk ($p = 0.24$, $\eta^2 = 0.16$), and the front squat ($p = 0.74$, $\eta^2 = 0.01$) (Table 7).

TABLE 6. Ratings of perceived exertion (RPE) ($N = 9$).

	Sleep loss	No sleep loss
Variable	Mean ± *SD*	Mean ± *SD*
RPE snatch	15.0 ± 1.4	14.9 ± 1.9
RPE clean and jerk	14.8 ± 1.9	15.6 ± 1.3
RPE front squat	16.2 ± 2.3	16.6 ± 2.4

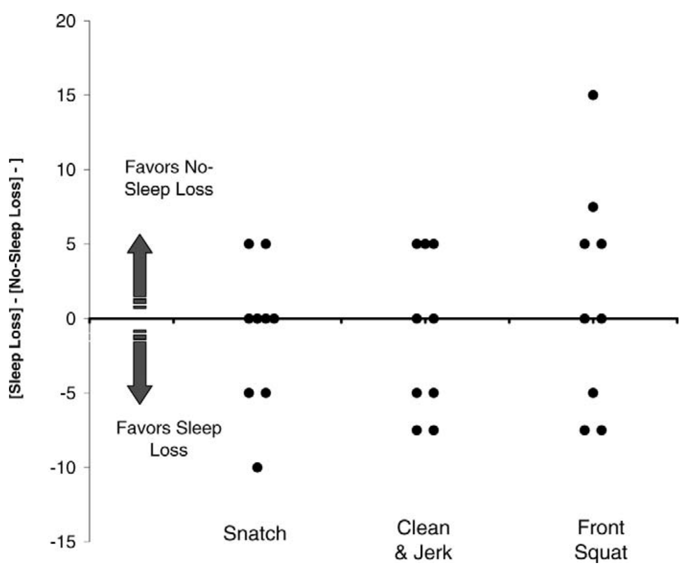

FIGURE 2. Difference between no sleep loss and sleep loss conditions. Difference score was calculated by subtracting the weight lifted during the sleep loss condition from the no sleep loss condition.

Figure 2 depicts the cortisol response to the sleep-deprived and the nonsleep-deprived conditions. No significant differences ($p = 0.98$, $1 - \beta = 0.05$, $\eta^2 = 0.00$) were noted between the two sleep conditions or for the group by time interaction ($p = 0.39$, $1 - \beta = 0.17$, $\eta^2 = 0.23$). However, significant differences ($p = 0.04$, $1 - \beta = 0.60$, $\eta^2 = 0.58$) were noted over time, with the pre-exercise value being significantly higher than the 1-hour postexercise ($p = 0.002$, $\eta^2 = 0.59$) and immediately postexercise values ($p = 0.025$, $\eta^2 = 0.35$) during the nonsleep-deprived condition. Additionally, the immediate postexercise value was significantly greater ($p = 0.04$, $\eta^2 = 0.30$)

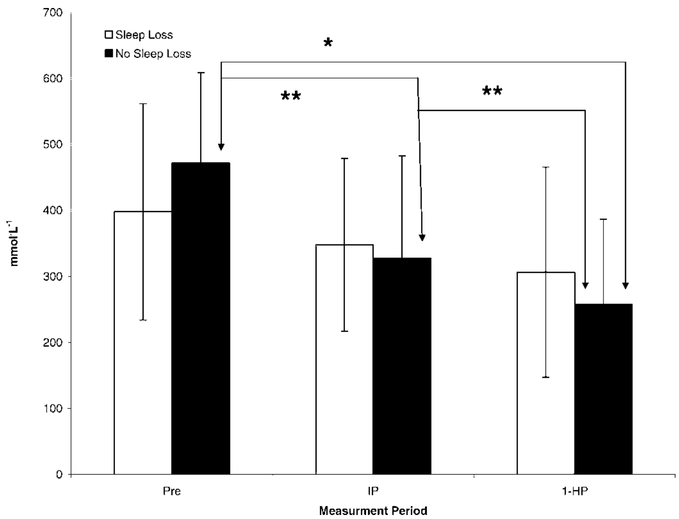

FIGURE 3. Cortisol response to sleep loss and no sleep loss. IP = immediately post-training; 1-HP = 1-hour posttraining; * $p < 0.05$; ** $p < 0.01$.

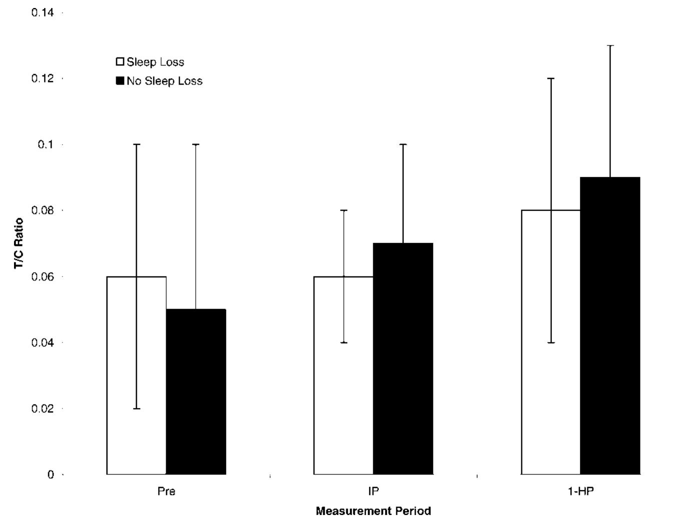

FIGURE 5. Testosterone/cortisol ratio response to sleep loss or no sleep loss. IP = immediately posttraining; 1-HP = 1-hour posttraining.

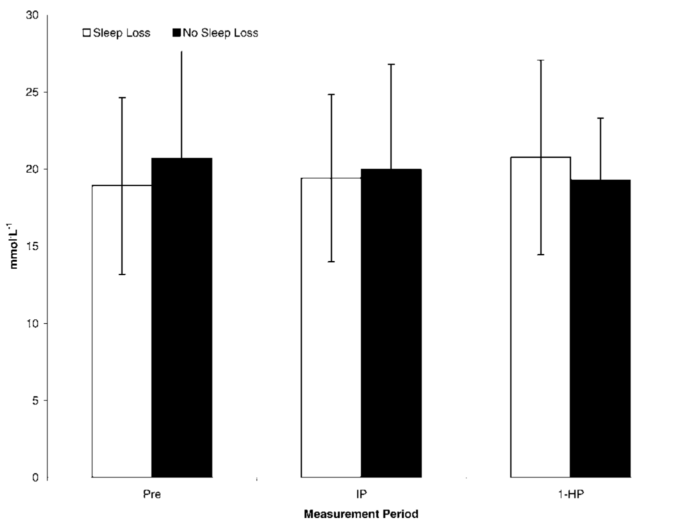

FIGURE 4. Testosterone response to sleep loss or no sleep loss. IP = immediately post-training; 1-HP = 1-hour posttraining.

than the 1-hour postexercise cortisol value during the nonsleep-deprived condition (Figure 3).

The testosterone response to sleep-deprived and the nonsleep-deprived condition is presented in Figure 4. No significant differences were determined between the conditions ($p = 0.77$, $1 - \beta = 0.06$, $\eta^2 = 0.01$), over the testing time period ($p = 0.94$, $1 - \beta = 0.06$, $\eta^2 = 0.02$), or for the condition by time interaction ($p = 0.21$, $1 - \beta = 0.28$, $\eta^2 = 0.36$). Additionally, when the T/C ratio was evaluated, no significant differences existed between conditions ($p = 0.79$, $1 - \beta = 0.07$, $\eta^2 = 0.01$), over time ($p = 0.06$, $1 - \beta = 0.56$, $\eta^2 = 0.56$), or for the condition by time interaction ($p = 0.75$, $1 - \beta = 0.08$, $\eta^2 = 0.09$). A summary of the T/C ratio response is presented in Figure 5.

DISCUSSION

The primary finding in this investigation is that 24 hours of sleep loss does not affect weightlifting performance during a high intensity training session. In the present investigation 1RM weights determined during the performance of the snatch, clean and jerk, and front squat were unaltered by the amount of sleep received the night prior to the training session. These findings are in general agreement with the findings of Reilly et al. (47) where one night of partial sleep deprivation did not affect maximal lifting performance in the biceps curl, bench press, leg press, and dead lift. The present study differs slightly from that of Reilly et al. (47) in that it utilizes a complex task that has a large skill component, which was hypothesized to accentuate the effects of the acute period of sleep loss. This hypothesis was based upon the data that suggest that the performance of less skilled tasks are not as affected by periods of sleep loss than more complex motor skills (47). However, while the present study employed a series of complex motor tasks, the 24-hour period of sleep loss may not have been long enough to induce the expected performance decrements.

Generally, the literature suggests that the effects of <30 hours of sleep loss have resulted in no significant alterations in markers of physical performance (11, 32, 46, 47). When examining other anaerobic activities such as the Wingate Anaerobic cycle, test performance decrements are typically absent with acute periods of sleep loss, which range from 4–60 hours (6, 33, 51, 54). Conversely, some researchers have noted decrements in Wingate performance with acute periods of sleep loss as short as 36 hours. Additionally, when looking at the effects of acute periods of sleep loss (60 hours) on other markers of anaerobic performance, such as the vertical jump and isokinetic knee extension strength, decreased performance has been noted (55). Based upon the current body of knowledge, the lack of performance impairments found in the present study may have occurred in response to a relatively short period of sleep deprivation. It is likely that extending the period of sleep deprivation or utilizing multiple days of partial sleep loss would have resulted in decrements in performance.

Several studies have reported a decrease in performance following a period of sleep deficit (7, 9, 26, 32, 55, 56). Thirty hours of sleep loss combined with intermittent exercise significantly decreased isokinetic knee extension peak torque at 1.57, 2.62, and 3.66 rad·sec^{-1} and for knee flexion peak torque at 1.57 rad·sec^{-1} (7). Sixty-four hours of sleep loss resulted in significant decrements in knee extension torque at 60 and 180°·sec^{-1} (55). Interestingly, when sleep loss was not combined with exercise, knee extension torque significantly decreased at 1.57, 2.62, and 3.66 rad·sec^{-1} (7) and at 60°·sec^{-1} (55). Sleep loss has also been reported to result in significantly increased 40-yard sprint time (9), decreased vertical jump height (55), back strength (32), and isometric grip strength (26, 56).

Many authors speculated that the decrease in exercise performance is due to a decrease in arousal and diminished motivation (28, 47, 54, 55). Decreases in mood states often occur before physical performance decrements, particularly if there is extrinsic motivation to succeed (38). Confusion, fatigue, vigor, and total mood disturbance were all negatively affected by sleep deprivation in the present study. These changes in mood are in broad agreement with previous studies (27, 30, 32, 47). Additionally, feelings of fatigue were increased due to the intensity of the workout protocol even though the subjects were accustomed to this type of training.

Interestingly, in the present investigation subjective sleepiness was not altered after 24 hours of sleep deprivation. This result is in disagreement with previous findings (27, 30, 46, 47) where the perception of sleepiness was increased following varying periods of sleep loss. The findings of this investigation could have been due to the novelty and anticipation of the exercise after the sleep deprivation situation (20). Following the exercise bout, feelings of sleepiness were decreased in the nonsleep-deprived conditioned subjects and were unaffected in the sleep-deprived subjects. Similar results were reported in other studies where exercise did not affect sleepiness in sleep-deprived subjects from pre-exercise to postexercise (27, 47). The lack of change in the perception of sleepiness experienced by the sleep-deprived subjects may have occurred because of the combination of the lack of sleep and the fatigue associated with the weightlifting protocol.

An increase in the perception of effort or RPE following a bout of maximal exercise in a sleep-deprived state should not be affected unless there is a highly technical component to the exercise, or the movement requires a base level of skill not yet mastered by the subject. Ratings of perceived exertion in the present study were unaffected by sleep deprivation after the performance of maximal attempts in the snatch, clean and jerk, and front squat. This finding is in agreement (34) with a related study where maximal exercise was performed. The findings of a lack of increase in RPE in the current study might be expected as the subjects were technically proficient at performing the exercises utilized. Another possible reason often reported in the literature for the occurrence of an increase in RPE in response to sleep deprivation could be due to the increase in fatigue and sleepiness that usually occurs following a period of sleep deprivation, or to the perceived notion that sleep loss will decrease performance (29). Therefore, another possible reason for a lack of increase in the subjects' RPE may be linked to a lack of change in the subjects' sleepiness as determined by the subjective sleepiness measurement scale.

Following a period of sleep deprivation, cortisol concentrations have been reported to increase (37, 44), decrease (2), or remain unaltered (24, 30, 36). The cortisol response generally fluctuates according to the length of the training session and amount of volume and/or intensity prescribed. After an acute resistance training bout, cortisol concentrations have been reported to increase (12, 15, 25), decrease (15), or remain unaffected (12, 39, 43). During this investigation, cortisol concentrations decreased immediately after exercise and 1 hour postexercise when compared to pre-exercise levels in the nonsleep-deprived condition. This finding is similar to that found by Häkkinen et al. (15) who postulated that the decrease in serum cortisol concentrations can be explained by diurnal variation (10), which could have masked the possible increase. Additionally, the decrease in cortisol concentrations agrees with Akerstedt et al. (2) who discovered a significant decrement in serum cortisol after 48 hours of sleep deprivation. Therefore, it appears that sleep deprivation by itself does not result in an increased activation of cortisol secretion (2), but the response remains equivocal.

Following a period of sleep deprivation, the testosterone response to an ensuing exercise bout appears to decrease (1, 2, 35, 36). The testosterone response also varies according to length of training session and amount of volume and/or intensity prescribed. Testosterone concentrations increase (12, 15, 25, 43), decrease (15), or remain unaffected (12, 39, 43) following an acute resistance training bout. Neither sleep deprivation nor the weightlifting protocol altered the testosterone concentration in the current study. This was probably a result of the nature of the exercise regime (high-intensity, moderate volume) as the program was very similar to that used by other investigators who also found no change in testosterone concentrations (12, 39, 43). Similarly, testosterone concentrations may have been blunted by a combination of two factors: diurnal variation (8) which could have obscured the possible increase, and the effect of sleep deprivation which could have masked the possible decrease. Additionally, the T/C ratio was not affected by the sleep condition or the workout protocol, which is to be expected following a typical weightlifting workout (39).

In conclusion, it has long been thought that sleep loss creates a stressful situation that significantly impacts athletic performance. However, the results from acute sleep loss studies do not seem to support the theory in a physiological sense. The majority of adverse effects are found in the psychological variables relating to performance. Bonnet (4) theorized that motivation is a key marker in the validity of tests of anaerobic power and capacity since sleep deprivation mainly affects the higher central nervous system cognitive center. Symons et al. (53) concluded that subjects who undergo acute periods of sleep loss for 60 hours can react as fast, and with as much force, as those who have had a regular night of sleep. Therefore, the substantial psychological alterations and lack of physiological changes following periods of sleep loss support the theory that sleep serves primarily the brain.

Practical Applications

These data indicate that acute periods of sleep loss will not negatively alter the physiological capabilities of an athlete involved in short-term maximal efforts. Preceding a competition, athletes are capable of performing very well as long as they are intensely focused on the task at hand. The athletes can be successful if they are sufficiently mentally motivated.

Additionally, coaches need to be aware of their athlete's sleep status. Traveling, different sleeping environments, cutting weight, and precompetition anxiety can all disturb an athlete's sleep. If an athlete is in a state of sleep debt, as noticed by negative mood disturbances, it may be more beneficial to focus on the psychological (motivation) rather than the physiological aspect of the sport.

REFERENCES

1. AAKVAAG, A., T. SAND, P.K. OPSTAD, AND F. FONNUM. Hormonal changes in serum in young men during prolonged physical strain. *Eur. J. Appl. Physiol.* 39:283–291. 1978.
2. AKERSTEDT, T., J. PALMBLAD, B. DE LA TORRE, R. MARANA, AND M. GILLBERG. Adrenocortical and gonadal steroids during sleep deprivation. *Sleep* 3:23–30. 1980.
3. ATKINSON, G., T. REILLY, J. WATERHOUSE, AND S. WINTERBURN. Pharmacology and the travelling athlete. In: *The Clinical Pharmacology of Sport and Exercise.* T. Reilly and M. Orme, eds. Amsterdam: Elsevier Science, 1997. pp. 293–301.
4. BONNET, M.H. Sleep, performance and mood after the energy-expenditure equivalent of 40 hours of sleep deprivation. *Psychophysiology* 17:56–63. 1980.
5. BORG, G. Perceived exertion as an indicator of somatic stress. *Scand. J. Rehabil. Med.* 2:92–98. 1970.
6. BRYANT, W.K., D.W. HILL, AND J.C. SMITH. Sleep deprivation: No effect on anaerobic power and capacity [Abstract]. *Med. Sci. Sports Exerc.* 23: S11. 1991.
7. BULBULIAN, R., J.H. HEANEY, C.N. LEAKE, A.A. SUCEC, AND N.T. SJOHOLM. The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. *Eur. J. Appl. Physiol.* 73:273–277. 1996.
8. CLAIR, P., B. CLAUSTRAT, D. JORDAN, H. DECHAUD, AND G. SASSOLAS. Daily variations of plasma sex hormone-binding globulin binding capacity, testosterone and luteinizing hormone concentrations in healthy rested adult males. *Horm. Res.* 21:220–223. 1985.
9. COPES, K., AND J. ROSENTSWIEG. The effects of sleep deprivation upon motor performance of ninth-grade students. *J. Sports Med. Phys. Fitness* 12:47–53. 1972.
10. FOLLENIUS, M., AND G. BRANDENBERGER. Plasma free cortisol during secretory episodes. *J. Clin. Endocrinol. Metab.* 62:609–612. 1986.
11. GOH, V.H., T.Y. TONG, C.L. LIM, E.C. LOW, AND L.K. LEE. Effects of one night of sleep deprivation on hormone profiles and performance efficiency. *Mil. Med.* 166:427–431. 2001.
12. HÄKKINEN, K., AND A. PAKARINEN. Acute hormonal responses to two different fatiguing heavy-resistance protocols in male athletes. *J. Appl. Physiol.* 74:882–887. 1993.
13. HÄKKINEN, K., A. PAKARINEN, M. ALEN, H. KAUHANEN, AND P.V. KOMI. Daily hormonal and neuromuscular responses to intensive strength training in 1 week. *Int. J. Sports Med.* 9:422–428. 1988.
14. HÄKKINEN, K., A. PAKARINEN, M. ALEN, H. KAUHANEN, AND P.V. KOMI. Neuromuscular and hormonal adaptations in athletes to strength training in two years. *J. Appl. Physiol.* 65:2406–2412. 1988.
15. HÄKKINEN, K., A. PAKARINEN, M. ALEN, H. KAUHANEN, AND P.V. KOMI. Neuromuscular and hormonal responses in elite athletes to two successive strength training sessions in one day. *Eur. J. Appl. Physiol.* 57:133–139. 1988.
16. HÄKKINEN, K., A. PAKARINEN, M. ALEN, AND P.V. KOMI. Serum hormones during prolonged training of neuromuscular performance. *Eur. J. Appl. Physiol.* 53:287–293. 1985.
17. HELLMICH, N. Too many students will cheat on sleep. *USA Today*, March 24, 1999.
18. HODDES, E., W. DEMENT, AND V. ZAROCHE. Development and use of the Stanford Sleepiness Scale. *Psychophysiology* 9:150. 1971.
19. HOLM, S. A simple sequentially rejective multiple test procedure. *Scand. J. Statistics* 6:65–70. 1979.
20. HORNE, J.A. A review of the biological effects of total sleep deprivation in man. *Biol. Psychol.* 7:55–102. 1978.
21. HORNE, J.A., AND O. ÖSTBERG. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int. J. Chronobiol.* 4:97–110. 1976.
22. JACKSON, A.S., AND M.L. POLLOCK. Generalized equations for predicting body density of men. *Br. J. Nutr.* 40:497–504. 1978.
23. JONES, L. *USWF Coaching Accreditation Course: Senior Coach Manual.* Colorado Springs, CO: United States Weightlifting Federation, 1991.
24. KOLLAR, E.J., G.R. SLATER, J.O. PALMER, R.F. DOCTOR, AND A.J. MANDELL. Stress in subjects undergoing sleep deprivation. *Psychosom. Med.* 28:101–113. 1966.
25. KRAEMER, W.J., A.C. FRY, B.J. WARREN, M.H. STONE, S.J. FLECK, J.T. KEARNEY, B.P. CONROY, C.M. MARESH, C.A. WESEMAN, N.T. TRIPLETT, AND S.E. GORDON. Acute hormonal responses in elite junior weightlifters. *Int. J. Sports Med.* 13:103–109. 1992.
26. LEGG, S.J., AND J.F. PATTON. Effects of sustained manual work and partial sleep deprivation on muscular strength and endurance. *Eur. J. Appl. Physiol.* 56:64–68. 1987.
27. MARTIN, B., AND R. HANEY. Self-selected exercise intensity is unchanged by sleep loss. *Eur. J. Appl. Physiol.* 49:79–86. 1982.
28. MARTIN, B.J. Effect of sleep deprivation on tolerance of prolonged exercise. *Eur. J. Appl. Physiol.* 47:345–354. 1981.
29. MARTIN, B.J. Sleep deprivation and exercise. *Exerc. Sport Sci. Rev.* 14: 213–229. 1986.
30. MARTIN, B.J., P.R. BENDER, AND H. CHEN. Stress hormonal response to exercise after sleep loss. *Eur. J. Appl. Physiol.* 55:210–214. 1986.
31. MCNAIR, D., M. LORR, AND L. DROPPELMAN. *EITS Manual for the Profile of Mood States.* San Diego, CA: Educational and Industrial Testing Service, 1971.
32. MENEY, I., J. WATERHOUSE, G. ATKINSON, T. REILLY, AND D. DAVENNE. The effect of one night's sleep deprivation on temperature, mood, and physical performance in subjects with different amounts of habitual physical activity. *Chronobiol. Int.* 15:349–363. 1998.
33. MOUGIN, F., H. BOURDIN, M.L. SIMON-RIGAUD, J.M. DIDIER, G. TOUBIN, AND J.P. KANTELIP. Effects of a selective sleep deprivation on subsequent anaerobic performance. *Int. J. Sports Med.* 17:115–119. 1996.
34. MYLES, W.S. Sleep deprivation, physical fatigue, and the perception of exercise intensity. *Med. Sci. Sports Exerc.* 17:580–584. 1985.
35. OPSTAD, P.K., AND A. AAKVAAG. Decreased serum levels of oestradiol, testosterone and prolactin during prolonged physical strain and sleep deprivation, and the influence of a high calorie diet. *Eur. J. Appl. Physiol.* 49:343–348. 1982.
36. OPSTAD, P.K., AND A. AAKVAAG. The effect of sleep deprivation on the plasma levels of hormones during prolonged physical strain and calorie deficiency. *Eur. J. Appl. Physiol.* 51:97–107. 1983.
37. OPSTAD, P.K., A. AAKVAAG, AND T.O. ROGNUM. Altered hormonal response to short-term bicycle exercise in young men after prolonged physical strain, caloric deficit, and sleep deprivation. *Eur. J. Appl. Physiol.* 45:51–62. 1980.
38. OPSTAD, P.K., R. EKANGER, M. NUMMESTAD, AND N. RAABE. Performance, mood, and clinical symptoms in men exposed to prolonged, severe physical work and sleep deprivation. *Aviat. Space Environ. Med.* 49:1065–1073. 1978.
39. PASSELERGUE, P., A. ROBERT, AND G. LAC. Salivary cortisol and testosterone variations during an official and a simulated weight-lifting competition. *Int. J. Sports Med.* 16:298–303. 1995.
40. PEEKE, S.C., E. CALLAWAY, R.T. JONES, G.C. STONE, AND J. DOYLE. Combined effects of alcohol and sleep deprivation in normal young adults. *Psychopharmacology (Berl)* 67:279–287. 1980.
41. PILCHER, J.J., AND A.I. HUFFCUTT. Effects of sleep deprivation on performance: A meta-analysis. *Sleep* 19:318–326. 1996.
42. PORTER, J.M., AND J.A. HORNE. Exercise and sleep behaviour. A questionnaire approach. *Ergonomics* 24:511–521. 1981.
43. RAASTAD, T., T. BJORO, AND J. HALLEN. Hormonal responses to high- and moderate-intensity strength exercise. *Eur. J. Appl. Physiol.* 82:121–128. 2000.
44. RADOMSKI, M.W., L.E. HART, J.M. GOODMAN, AND M.J. PLYLEY. Aerobic fitness and hormonal responses to prolonged sleep deprivation and sustained mental work. *Aviat. Space Environ. Med.* 63:101–106. 1992.
45. REILLY, T., G. ATKINSON, AND J. WATERHOUSE. *Biological Rhythms and Exercise.* Oxford, England: Oxford University Press, 1997.
46. REILLY, T., AND T. DEYKIN. Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. *J. of Hum. Move. Stud.* 9:157–170. 1983.
47. REILLY, T., AND M. PIERCY. The effect of partial sleep deprivation on weight-lifting performance. *Ergonomics* 37:107–115. 1994.
48. RODGERS, C.D., D.H. PATERSON, D.A. CUNNINGHAM, E.G. NOBLE, F.P. PETTIGREW, W.S. MYLES, AND A.W. TAYLOR. Sleep deprivation: Effects on work capacity, self-paced walking, contractile properties and perceived exertion. *Sleep* 18:30–38. 1995.
49. SHEPHARD, R.J. Sleep, biorhythms and human performance. *Sports Med.* 1:12–27. 1984.
50. SIRI, W. Body composition from fluid spaces and density: Analysis of methods. In: *Techniques for Measuring Body Composition.* J. Brozek and A. Henschel, eds. Washington: National Academy of Sciences, 1961. pp. 223–224.
51. SOUISSI, N., B. SESBOUE, A. GAUTHIER, J. LARUE, AND D. DAVENNE. Effects of one night's sleep deprivation on anaerobic performance the following day. *Eur. J. Appl. Physiol.* 89:359–366. 2003.
52. STONE, M.H., AND H.S. O'BRYANT. *Weight Training: A Scientific Approach.* Minneapolis, MN: Burgess International, 1987.
53. SYMONS, J.D., D.G. BELL, J. POPE, T. VANHELDER, AND W.S. MYLES. Electro-mechanical response times and muscle strength after sleep deprivation. *Can. J. Sport Sci.* 13:225–230. 1988.
54. SYMONS, J.D., T. VANHELDER, AND W.S. MYLES. Physical performance and physiological responses following 60 hours of sleep deprivation. *Med. Sci. Sports Exerc.* 20:374–380. 1988.
55. TAKEUCHI, L., G.M. DAVIS, M. PLYLEY, R. GOODE, AND R.J. SHEPHARD. Sleep deprivation, chronic exercise and muscular performance. *Ergonomics* 28:591–601. 1985.

56. Thomas, V., and T. Reilly. Circulatory, psychological and performance variables during 100 hr of paced continuous exercise under conditions of controlled energy intake and work output. *J. of Hum. Move. Stud.* 1:149–156. 1975.
57. Van Beaumont, W. Red cell volume with changes in plasma osmolarity during maximal exercise. *J. Appl. Physiol.* 35:47–50. 1973.
58. Vanhelder, T., and M.W. Radomski. Sleep deprivation and the effect on exercise performance. *Sports Med.* 7:235–247. 1989.
59. Wallace, J. Principles of Cardiorespiratory Endurance Programming. In: *ACSM'S Resource Manual for Guidelines for Exercise Testing and Prescription.* L.A. Kaminsky, K.A. Bonzheim, C.E. Garber, S.C. Glass, L.F. Hamm, H.W. Kohl, and A. Mikesky, eds. Baltimore, MD: Lippincott Williams & Williams, 2006. pp. 336–349.
60. Walters, P.H. Sleep, the athlete, and performance. *Strength Cond. J.* 24(2):17–24. 2002.
61. Waterhouse, J., T. Reilly, and B. Edwards. The stress of travel. *J. Sports Sci.*22:946–965. 2004.
62. Webb, W.B., and H.W. Agnew, Jr. Effects on performance of high and low energy-expenditure during sleep deprivation. *Percept. Mot. Skills* 37: 511–514. 1973.

Acknowledgments

This study was funded by a National Strength and Conditioning Association Student research award. The authors of this project would like to thank Dr. William Kraemer at the University of Connecticut for his assistance with interpreting the hormonal measurements. Additionally, the authors would like to thank all of the subjects who participated in this study and all who assisted with the rigors of data collection involved with this project.

Address correspondence to G. Gregory Haff, ghaff@hsc.wvu.edu.