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Research article

Weekly Fluctuations in Subjective and Objective Measures of Internal Training Load and Their Relationships in Male Elite Rowers

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Abstract

Subjective and objective methods are commonly used to evaluate the load and physiological adaptations of athletes in training. However, there is a lack of data and their relationship concerning these tools in professional rowing training. This study aimed to investigate the relationship between the subjective and objective training loads of male rowers during a mesocycle. Field data were collected from 26 professional rowers over 6 consecutive weeks. Subjective training load variables (perceived exertion, acute: chronic workload ratio, training monotony and strain), and objective variables (white blood cell, red blood cell, blood urea, creatine kinase, testosterone, and cortisol) was collected, and correlations between various TL's were analyzed. All participants completed 6 weeks of training, which consisted of resistance (315 ± 88.5min/week), on-water (817.5 ± 9min/week), ergometer (341.9 ± 194.1min/week) and functional training (60min/week). Week 5 had the highest average weekly subjective training load (10849.23 ± 1361.14 AU), whereas Week 2 showed the highest training monotony (TM) with statistically significant differences compared to Week 1, week 3, week 5 and week 6 ($p < 0.05$), with small to moderate effect sizes (ES: 0.275 - 0.619). There were correlations among all the subjective training load variables. A positive correlation was found between $sRPE_{TL}$ and TS ($r = 0.80$). Blood urea (BU) was positively correlated with weekly $sRPE_{TL}$ ($r = 0.44$, $p < 0.05$), TM ($r = 0.40$, $p < 0.05$), TS ($r = 0.43$, $p < 0.05$) and ACWR ($r = 0.44$, $p < 0.05$). Similarly, creatine kinase (CK) was also associated with these indicators ($r = 0.50 - 0.60$). Testosterone and cortisol showed a consistently negative correlation ($r = -0.64$), but no relationship were found between these hormones and subjective training load. In conclusion, this study demonstrates a significant correlation between subjective and objective training loads in elite rowers. Our findings provide empirical evidence that ACWR, TM and TS serve as sensitive indicators of biochemical markers (CK and BU) fluctuations in professional rowing athletes. Given the correlation between the above objective and subjective indicators, coaches can adjust the training schedules based on the subjective data during training week, and combine with hematological tests to further promote positive adaptations.

Key words: Session rating of perceived exertion, subjective and objective load, internal load, training monitoring.

Introduction

In the process of scientific development of sports training, researchers continue to explore the critical value of training load to improve sports performance, resulting in a 20-25% increase om athlete load over the past decade (Hackney et al., 2016; Gdovin et al., 2023). Excessive training load may lead to negative results such as mental and physical fatigue (Soligard et al., 2016), while insufficient duration and intensity of the load can result in inadequate adaptation, limiting improvements in athlete performance (Gabbett and Oetter, 2024). Traditionally, training load is measured using metrics such as time, distance, power, velocity, acceleration, and global positioning systems (GPS), which objectively quantify the external training load (Ravé et al., 2020); Regarding internal load quantification, key physiological parameters including heart rate, blood lactate, and oxygen consumption have been established as reliable objective measurement indicators. Simultaneously, each athlete may respond uniquely to a given training load. It can also be measured using subjective methods such as through the session rating of perceived exertion(sRPE) scale. Additional variables derived from sRPE, such as the acute: chronic workload ratio (ACWR), training monotony(TM), and training strain(TS), can provide further insight into both positive and negative training outcomes (Nakaoka et al., 2021). Gabbett (2016) suggested that the "sweet spot" and "danger zone" are useful for identifying potential injury risks and promoting positive adaptations. However, it remains unclear how these measurements relate to objective data.

In rowing training research, external loads are mostly described and quantified through distance or duration of training. When such metric is used, endurance training at intensities corresponding to < 2 $mmol \cdot L^{-1}$ blood lactate can make the total amount of training seem too high. As a result, recent studies have primarily described training loads of different intensities based on specific intensity intervals. The TRIMP method, based on heart rate, has also been widely used. However, factors such as hydration, temperature and fatigue can interfere with heart rate measurements (Van Erp et al., 2019), creating an urgent need for non-invasive, convenient and efficient subjective methods in long-term load monitoring (Scott et al., 2013). The sRPE scale and its derived metrics hold significant value in monitoring training loads (Haddad et al., 2017). Furthermore, the comparative analysis of sRPE with objective metrics facilitates a more holistic assessment of training loads, enables precise modulation of external training parameters to optimize internal load responses, and contributes to the prevention of training-related maladaptation, including overreaching (OR) and overtraining syndrome (OTS). Current studies suggest that a subjective approach may be superior to an objective one (Saw et al., 2015), and further research indicates that load parameters from

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different sources may provide a more comprehensive insight. Thus, combining subjective and objective training load variables is essential for comprehensively monitoring athletes' training responses (Montull et al., 2022). Despite the growing body of research on training load monitoring in sports science, there remains a paucity of evidence regarding the longitudinal assessment of both objective and subjective training loads in rowers throughout a mesocycle. Moreover, the relationships between various training load indicators in elite rowing athletes have not been sufficiently elucidated. Therefore, the aim of this study was (a) to quantify the subjective and objective training loads using sRPE and blood parameters, respectively, in elite male rowers during a mesocycle. (b) to describe and compare the weekly fluctuations of TM, TS, and ACWR derived from sRPE across different periods of a training mesocycle and (c) to determine the associations between weekly changes in hematological parameters and subjective training load variables in training
situations. Accordingly, we hypothesized that subjective and objective indicators can identify differences in different weekly loads and the cumulative training load over time. Furthermore, ACWR, TM and TS calculated from sRPE are associated with athletes'' hematological indicators, and the nature of these association varies. The findings of this study may provide new insights into athlete monitoring.

Methods

Study design

An observational and longitudinal study was adopted. Subjective and objective training load data were collected in each training session during a 6-week mesocycle from November 4, 2024 to December 2, 2024. The weekly schedule of the training program is shown in Table 1, and a detailed example of a training week is provided in Table 2.

Participants

Twenty-eight male athletes from Shannxi Water Sports Management Centre in Yangling, China, were initially recruited through convenient sampling. Two participants withdrew from the study for personal reasons. The final data included 26 participants who were 21.7 ± 3.6 years old, a height of 194.1 ± 2.45 cm, and a weight of 91.8 ± 5.4 kg. The absolute value of VO_{2max} at the most recent measurement was 6110.6 ± 459.3(ml·min^{-1}), and the relative value was 64.5 ± 6.1(ml·min^{-1}·kg^{-1}). The study protocol was approved by the ethics committee of XX university of physical education and sports (No.2025A015). Prior to study initiation, all participating athletes were thoroughly briefed on the research objectives, experimental protocols, requirements, and potential risks of the study and subsequently provided written informed consent.

Procedures

The data of subjective and objective loads were collected during a 6-week ***mesocycle*** from November, 2024 to December, 2024. All participants completed 6 weeks of training, which consisted of strength (315 ± 88.5 min/week), aquatic (817.5 ± 9 min/week), ergometer (341.9 ± 194.1 min/week) and functional training (60 min/week). All training sessions were systematically designed and supervised by the coaching staff, while researchers were responsible for recording initial observations and collecting sRPE data within 30 min post-session, where athletes resided in shared double-occupancy rooms (assigned by coaching staff) and adhered to a standardized protocol requiring mobile phone surrender after 22:30 daily. Prior to data collection, participants underwent comprehensive familiarization sessions for both venipuncture procedures and sRPE scale administration. Throughout the investigation period, all training variables were systematically computed and analyzed on a weekly basis.

Subjective training load monitoring

Athletes were monitored daily for their $_{s}$RPE using the CR-10 Borg's scale (Borg, 1970), adapted by Foster et al. (2001). Following a standardized 30-minute post-training recovery period, athletes quantitatively assessed their RPE using a validated mobile application. The $sRPE_{TL}$ was computed by multiplying the RPE by the total session duration (in min). Subsequently, the following variables were calculated: (1) the subjective training load, the sum of $sRPE_{TL}$ throughout the week; (2) ACWR, the ratio of

Table 1. Detailed description of the training program.

	Resistance (min)	On-water(min)	Ergometer(min)	TD/km
Week1	240	845	230	140
Week2	240	940	280	155
Week3	240	995	350	180
Week4	360	1025	270	165
Week5	450	700	320	135
Week6	360	400	250	85

TD: total distance

Table 2. Detailed example of training week1

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
6:00 a.m.	Hematological test	Ergometer 16km	On-water 20km	Ergometer 6km×3	On-water 14km	On-water 20km	OFF
9:30 a.m.	On-water 16km				Core		
3:00 p.m.	RT 120min	On-water 20km	OFF	RT 120min	On-water 16km	OFF	
7:00 p.m.	FT 30min	OFF	FT 30min	OFF	OFF		

RT: resistance training; FT: functional training.

weekly subjective training load and rolling average of weekly subjective training load in the preceding 4 weeks; (3) TM, determined by dividing the mean $sRPE_{TL}$ achieved across all training sessions of the week by the standard deviation(SD); and (4) TS, determined by multiplying $sRPE_{TL}$ by TM. Throughout the duration of the study, all variables were computed on a weekly basis.

$$sRPE_{TL} = sRPE \times t(min)$$
$$TM = sRPE_{TL}/7 \div TL_{SD}$$
$$TS = sRPE_{TL} \times wTM$$
$$ACWR = sRPE_{AL} \div sRPE_{CL}$$

T, training time (min); TL_{SD}, the standard deviation of training daily load in a week; TL, weekly training load; TM, training monotony; TS, training strain; AL, acute load; CL, chronic load.

Objective training load monitoring

In order to evaluate the functional state of athletes with a high degree of accuracy, it is necessary to make use of blood-based biomarkers. Examples of such biomarkers include lactate, blood urea(BU), and creatine kinase(CK). These biomarkers are already routinely utilized in numerous domains of elite sport. Their application can be categorized into two distinct but related functions: the first is the objective determination of the acute internal load, and the second is the estimation of the internal load through the assessment of tissue- or organ-specific stress or recovery processes. The present study employed objective training load as measured by hematological tests. Blood metrics were measured for each participant six weeks prior to the commencement of week 1. The average result for each participant was recorded as their baseline value. In order to regulate any possible dietary influences, the subjects were advised to remain in the care of a dietitian and abstain from consuming any additional nutritional supplements for the duration of their involvement in the study. To avoid circadian variation in responses, venous blood samples were taken following fasting in the early morning (6.00 am) following a day off. Three samples of 15 ml of blood were collected from the cephalic vein located in the antecubital fossa, and placed in tubes containing ethylenediaminetetraacetic acid (EDTA) without an anticoagulant for hematologic, biochemical, and hormonal analyses. White blood cells(WBC) and red blood cells(RBC) was detected by Beckman Coulter AC Tdiff-2 hemocytometer (Beckman Coulter, San Jose, CA, USA). A total of 2.5 ml of elbow vein blood was collected using a sodium heparin anti-coagulated vacuum blood collection tube for analyzing BU, CK, testosterone (T), and cortisol (C) (Beckman Coulter Access 2 Immunosav System; Beckman Coulter, San Jose, CA, USA). The collection, storage, processing, and analysis of blood samples was performed by a specialized team consisting of a sports medicine researcher and assistant researcher, both with experience in biochemical-hematological and hormonal tests.

Statistical analysis

Complete data were obtained for more than 90% of the training sessions. The remaining few training sessions were mainly due to technical errors, such as battery failure, abnormal blood lactate collection and analysis, resulting in extremely individual data loss. Descriptive statistics were used to characterize the sample. Results were presented as mean ± standard deviation (SD). The relationship between all subjective and objective variables at the mesocycle was verified using bivariate correlations (Pearson product moment correlation coefficient). The effect size of the correlations was determined by considering the following thresholds:< 0.1 = trivial; 0.1 - 0.3 = small; > 0.3 - 0.5 = moderate; > 0.5 - 0.7 = large; > 0.7 - 0.9 = very large; and > 0.9 = nearly perfect.

The present study investigated the relationship between the multivariate training load variables, in order to contrast between different weeks, a repeated measures ANOVA test was used to compare measures for periods of the six-week study, followed by the Bonferroni test for post-hoc comparisons if significant effects were observed. The results are significant for a $p \leq 0.05$. Hedge's g effect size (ES) was also calculated to determine the magnitude of pairwise comparisons. The Hopkins threshold was utilized are as follows: $g \leq 0.2$, trivial; $0.2 < g \leq 0.6$, small; $0.6 < g \leq 1.2$, moderate; $1.2 < g \leq 2.0$, large; $2.0 < g \leq 4.0$, very large; and $g > 4.0$, nearly perfect (Hopkins et al., 2009). The significance level was set at $\alpha = 0.05$, whereas the significance level in post-hoc tests was set at $p < 0.05$ divided by the number of pairwise comparisons. All data were analysed using IBM SPSS Statistics (version 22, IBM Corporation SPSS Inc., Chicago, IL).

Results

Weekly ACWR, TM, and TS are depicted in Table 3, Figure 1 and Figure 2. The $sRPE_{TL}$ remained elevated from week 1 to week 5, with a more substantial decrease occurring in week 6. Week 5 exhibited the highest average weekly internal training load, significantly higher than week 1 ($p < 0.001$; ES = 0.630) and week 2 ($p = 0.003$; ES = 0.287) with week six ($p < 0.001$; ES = 0.660).

The highest TM values were observed in Week 2, demonstrating statistically significant differences compared to Weeks 1, 3, 5, and 6 ($p < 0.05$), with small to moderate ES (0.275 - 0.619). This pattern suggests a more consistent training load distribution during the preceding 7 days, accompanied by an acute increase in training intensity during Week 2. Regarding TS, no significant inter-week differences were observed between weeks 2-5. However, following this period of consistent training, TS exhibited a progressive increase starting in week 6, ultimately reaching its maximal value. This can be attributed to the cumulative fatigue effect resulting from the preceding training weeks.

Weeks 2 and 3 of ACWR are approaching the 'Danger zone' set by previous studies (Blanch and Gabbett, 2016) (Figure 2). The sixth week is away from the 'Sweet Spot', meaning a lower training load in the recovery week. T concentrations demonstrated a biphasic pattern throughout the study period, characterized by an initial increase followed by a subsequent decline. Conversely, C levels showed a progressive elevation from week 1, corresponding with the intensification of training loads, and ultimately peaked during week 6 (Table 4).

Table 3. **The weekly subjective training load variables in participants during the mesocycle(AU).**

	sRPE_{TL}	TM	TS	ACWR
Week 1	7318.87 ± 1433.19†‡§||¶	1.54 ± 0.15†‡§||¶	11281.89 ± 2584.61†‡§||¶	0.90 ± 0.13†‡§||¶
Week 2	8801.84 ± 1895.78*¶	2.28 ± 0.39*‡||¶	19942.69 ± 4769.88*¶	1.37 ± 0.14*§||¶
Week 3	9030.67 ± 1821.09*§¶	1.91 ± 0.13*†	17290.55 ± 3825.34*¶	1.32 ± 0.11*||¶
Week 4	9872.67 ± 1795.44*¶	2.11 ± 0.51*	20605.98 ± 5475.55*¶	1.25 ± 0.07*†||¶
Week 5	10849.23 ± 1361.14*†¶	1.82 ± 0.13*†	19772.14 ± 2863.64*¶	1.11 ± 0.08*†¶
Week 6	7638.46 ± 1011.02‡§||	1.91 ± 0.15*†	14664.57 ± 2646.98*†‡§||	0.80 ± 0.06*†‡§||

sRPE_{TL}: weekly subjective training load; TM: training monotony; TS: training strain; ACWR: acute:chronic workload ratio. Values are means ± SD. *Significantly differences from week1 ($p < 0.05$); †Significantly differences from week2($p < 0.05$); ‡Significantly differences from week3 ($p < 0.05$); §Significantly differences from week4($p < 0.05$); ||Significantly differences from week5 ($p < 0.05$); ¶Significantly differences from week6 ($p < 0.05$).

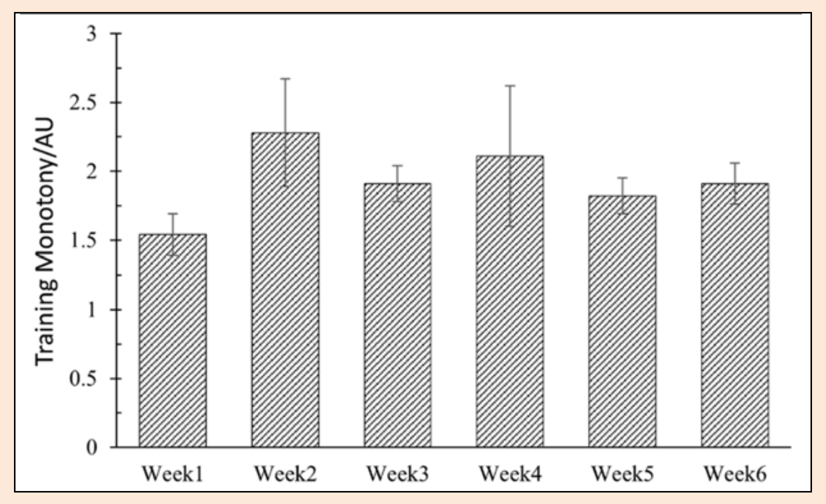


Figure 1. **TM variations calculated through the sRPE across 6 weeks.**

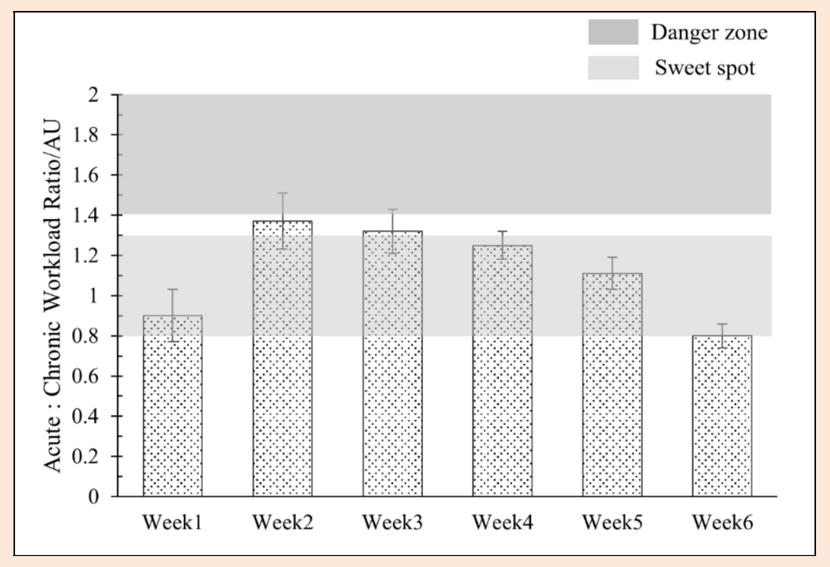


Figure 2. **ACWR variations calculated through the sRPE across 6 weeks.**

There is a correlation between all the sRPE-derived load metric (Figure 3). A positive correlation was found between sRPE_{TL} and TS ($r = 0.80$). BUN, a biochemical marker reflecting weekly training load variations, demonstrated significant positive correlations with sRPE_{TL} ($r = 0.44$, $p < 0.05$), TM ($r = 0.40$, $p < 0.05$), TS ($r = 0.43$, $p < 0.05$) and ACWR ($r = 0.44$, $p < 0.05$). Similarly, CK showed moderate to strong associations with these indicators ($r = 0.50 - 0.60$). C and T emerged as optimal biomarkers for monitoring athlete's physiological status and training responses. Although these hormones exhibited a consistent inverse relationship throughout the study period, no significant associations were observed with subjective load measures. This dissociation may be attributed to the high degree of individual variability characteristic of these endocrine markers.

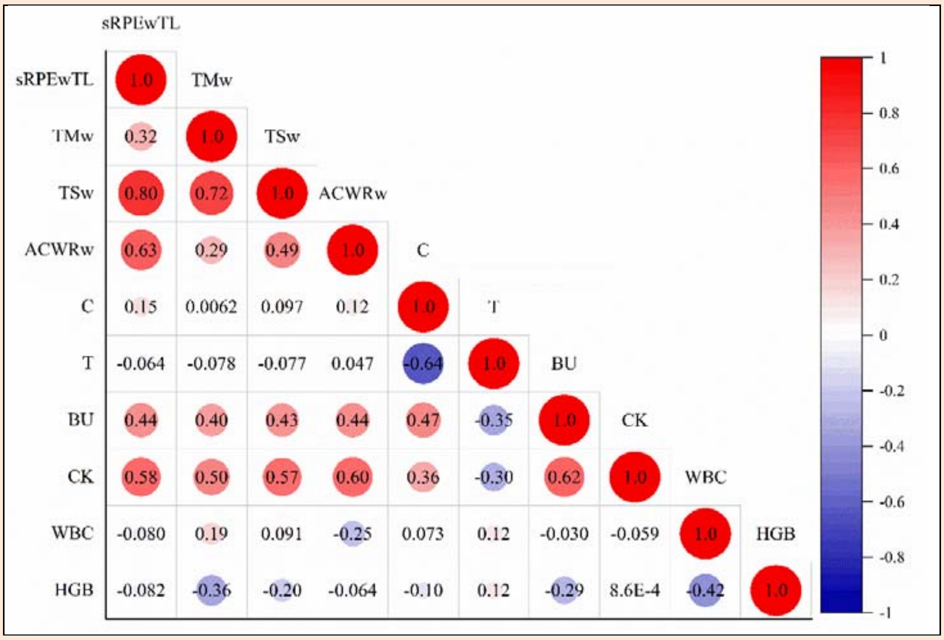
Discussion

This investigation systematically quantified both subjective and objective training loads in elite rowers throughout a six-week mesocycle. The findings demonstrated a significant positive correlation between subjective training load assessments, utilizing the sRPE method, and objective

Table 4. **Weekly fluctuations of hematological indicators.**

	C(μg/dL)	T(ng/dL)	BU(mg/dL)	CK(U/L)	WBC(10^9/L)	HGB(g/L)
Week 1	18.48 ± 4.72	506.58 ± 145.31	6.39 ± 0.79	232.69 ± 167.64	5.56 ± 1.84	152.46 ± 8.25
Week 2	22.36 ± 3.95	544.59 ± 148.00	7.57 ± 1.32	251.54 ± 91.78	6.22 ± 1.59	152.92 ± 8.23
Week 3	17.93 ± 2.44	576.09 ± 161.78	6.49 ± 0.78	218.34 ± 68.97	5.71 ± 1.29	153.12 ± 8.20
Week 4	18.5 ± 2.85	566.7 ± 147.17	6.9 ± 1.78	325.77 ± 111.52	5.68 ± 1.21	151.62 ± 6.44
Week 5	19.17 ± 2.76	575.55 ± 107.21	7.48 ± 1.74	324 ± 112.47	5.74 ± 1.54	153.69 ± 5.91
Week 6	18.66 ± 3.17	589.53 ± 112.98	5.64 ± 0.97	186.15 ± 69.70	6.01 ± 1.38	155.46 ± 15.94

Values are means ± SD. C, cortisol; T, testosterone; BU, blood urea; CK, creatine kinase; WBC, White blood cells; HGB, hemoglobin



	sRPEwTL	TMw	TSw	ACWRw	C	T	BU	CK	WBC	HGB
sRPEwTL	1.0									
TMw	0.32	1.0								
TSw	0.80	0.72	1.0							
ACWRw	0.63	0.29	0.49	1.0						
C	0.15	0.0062	0.097	0.12	1.0					
T	-0.064	-0.078	-0.077	0.047	-0.64	1.0				
BU	0.44	0.40	0.43	0.44	0.47	-0.35	1.0			
CK	0.58	0.50	0.57	0.60	0.36	-0.30	0.62	1.0		
WBC	-0.080	0.19	0.091	-0.25	0.073	0.12	-0.030	-0.059	1.0	
HGB	-0.082	-0.36	-0.20	-0.064	-0.10	0.12	-0.29	8.6E-4	-0.42	1.0

Figure 3. **Heat map of correlation coefficients between subjective and objective load indicators.** sRPEwTL, weekly subjective training load; TMw, training monotony; TSw, training strain; ACWRw, acute:chronic workload ratio; C, cortisol; T, testosterone; BU, blood urea; CK, creatine kinase; WBC, White blood cells; HGB, hemoglobin.

training load measures derived from hematological biomarker analysis. The positive correlation between training load indices was consistent with a previous study that reported a positive correlation between sRPE and the peak work rate in elite rowers (DellaValle and Haas, 2013). A study examined potential hormonal and psychological changes in elite male rowers during a 24-week preparatory period (Purge et al., 2006). A comparison of basal hormone concentrations with initial measurements revealed significant changes in testosterone and cortisol, as well as alterations in mean weekly training volume among the rowing athletes. Overall subjective stress was associated with testosterone, cortisol, and CK activity throughout the study period. The relationships between subjective and objective load monitoring are consistent with those observed in the present study. In professional athletes, internal training load was significantly correlated with sprint distance (Nobari et al., 2022), peak power during countermovement jumps (Rebelo et al., 2023), PlayerLoad and well-being (Kamarauskas et al., 2024). Given this information, subjective load derived from sRPE has the potential to provide valuable insights into changes in training load. Furthermore, it can effectively reflect objective training loads and recovery states.

The six-week mesocycle was structured according to standard rowing periodization principles, comprising an initial conditioning phase (Week 1), followed by four weeks of intensive training (Weeks 2-5), and concluding with an active recovery week (Week 6). This training block was characterized by consistently elevated training loads throughout the weekly cycles. This is common in the training of professional rowers (Tran et al., 2015), as the first phase of the competitive period focuses on a gradually increasing chronic loads (Debien et al., 2022), while the second week elevates training volume through prolonged technical and aerobic fitness training. Therefore, the goal of the training program is to enhance the athletes' performance by gradually increasing training load, adjusting it based on changes in the hematological parameters, and maintaining reasonable ACWR, TM and TS. The weekly internal training load in this group of rowers was higher than that reported for professional athletes (Della and Haas, 2013). This is likely because nearly half of the athletes and coaches who participated in this study were part of national training teams, leading to a rigorous training program. Each week included over 4 hours of strength training, extensive ergometer training, and on-water rowing when weather conditions allowed. During the final week's load tapering phase, the coaches strategically eliminated additional ergometer sessions and reduced training volume. Contrary to expectations, athletes' subjective training load remained elevated, potentially reflecting the residual effects of cumulative fatigue from previous training weeks, as evidenced by the sustained sRPE_{TL}. This situation should be considered in future training programs. Although coaches reduced the training load, this did not align with the subjective load changes perceived by athlete, suggesting that relying solely on objective indicators may fail to detect potential progressive fatigue (Fusco et al., 2020; Sanders et al., 2018).

An ACWR between 1.00 and 1.49 is associated with the lowest risk of injury compared to lower or higher values during a competitive season (Weiss et al., 2017). The training load appeared to be effectively managed in this study, as the average ACWR remained below the 1.5 threshold in most weeks. Because of the low internal training load in week 1, the ACWR peaked in week 2. A weekly training monotony greater than 2, indicating a lack of variation in training loads, has been associated with a significantly increased risk of injury and overtraining (Foster, 1998). In the present study, TM in weeks 2 and 4 were not well controlled, which may be related to the training program designed by the coaches. TS followed a similar trend to TM, increasing significantly in week 2 and peaking in week 4. While periodized training strategies typically recommend alternating high and low training loads to mitigate TS, the preparatory phase of rowing training necessitates sustained high-volume loads to optimize aerobic capacity development. This This physiological adaptation requirement consequently leads to systematically elevated TS levels throughout this specific training period.

Another finding from our study was that BU showed the strongest correlation with $sRPE_{TL}$; while ACWR showed the strongest correlation with CK. The synchronous increase in BU and CK with weekly loads suggests that the sRPE method can effectively reflect changes in the rowers' functional status. During a training microcycle involving various sessions, BU increased significantly with sRPE, consistent with the findings of Wahl et al., (2021). BU represents the terminal metabolite of amino acid and protein catabolism in the body. In elite athletes. elevated BU concentrations primarily result from increased energy substrate utilization and protein degradation through gluconeogenesis during prolonged, high-volume training sessions. The present study revealed a significant correlation between load and BU, indicating that sRPE serves as a valid and reliable method for measuring training volume.

CK serve as a crucial enzyme in cellular energy homeostasis, playing a pivotal role in intracellular energy metabolism, muscle contraction, and ATP regeneration processes. In sports medicine practice, CK activity has been established as a reliable biomarker for monitoring training load intensity and athletes' functional status. The physiological mechanism underlying CK elevation involves exercise-induced micro trauma to skeletal muscle cell membranes, resulting in the subsequent release of intracellular CK into the systemic circulation. This biochemical response typically manifests as elevated serum CK levels, reaching peak concentrations within 8-24 hours' post-exercise. The magnitude of CK elevation demonstrates a dose-response relationship with both exercise intensity and the degree of exercise-induced muscle damage, serving as a quantitative indicator of accumulated training stress. (Horta et al., 2019). Elevated CK levels before training or competition indicate maladaptation to the training load (Hunkin et al., 2014). Since the coaches adjusted the training schedule daily, no significant non-contact injuries occurred during the study. However, our findings suggest that higher ACWR is associated with elevated blood CK levels and subsequent neuromuscular fatigue.

Intense exercise significantly elevates oxygen consumption, resulting in the accumulation of substantial metabolites and free radicals within biological systems. This oxidative stress contributes to cellular membrane damage and induces microscopic tissue damage, particularly when subjected to singular or repetitive mechanical loading. Such physiological responses occur when the applied mechanical load surpasses the tissue's inherent strength and regenerative capacity. The progression of exercise-induced fatigue is closely associated with elevated serum CK activity, a well-established biomarker of muscle damage. Under the combined effects of stress and strain (Kalkhoven et al., 2021), the body experiences more pronounced neuromuscular fatigue. This fatigue manifests through multiple physiological pathways: diminished central nervous system excitability, impaired proprioceptive feedback from muscle ligaments, delayed musculoskeletal response times, reduced maximum strength output, compromised balance ability, and deteriorated limb movement control. Collectively, these neuromuscular alterations significantly elevate injury susceptibility. The observed cascade of neuromuscular adaptations to mechanical loading suggests that the predictive capacity of ACWR for injury risk may be mediated through two primary mechanisms: elevated CK concentrations and diminished load tolerance capacity. These findings underscore the complex interplay between biochemical markers and mechanical factors in exercise-related injury pathogenesis.

By monitoring athletes' loads, the ACWR method provides a simple and scientific quantitative tool for exploring the relationship between training loads and sports injuries. It ensures that training load changes are optimized and avoids dangerous load arrangements, thereby reducing the risk of injuries caused by excessive training and extending athletes' careers. Admittedly, ACWR has sparked significant controversy in peer-review research due to its lack of pathological evidence and methodological limitations (Impellizzeri et al., 2021). A comprehensive understanding of injury risk factors is essential for establishing causal relationships in sports medicine. While the current study provides a preliminary evidence supporting an association between ACWR and CK, further investigations are needed to substantiate this relationship and elucidate its underlying mechanisms.

This study has several limitations. First, due to logistical constraints, a formal sample size calculation was not performed. While the inclusion of all available participants from a single rowing team ensured consistency in training regimens and environmental factors, this approach may limit the generalizability of findings to populations with different training backgrounds or competitive levels. Second, the analysis was conducted at the team-level rather than accounting for individual athlete roles. Third, the exclusive focus on male professional rowers restricts the extrapolation of findings to female athletes or rowers at different competitive levels, as sex- and level-specific differences in training adaptation and injury risk profiles may exist.

Practical applications

The use of subjective and objective measures of training load in rowing appears advantageous for understanding training stress and optimizing physical preparation. Typically, hematological indicators were collected and analyzed after a week of training. Therefore, monitoring internal training load using sRPE-based approaches may enable more timely individual training prescriptions. Whilst external metrics cannot directly indicate fitness improvements from training loads, research on measuring external loads and their subjective costs has positively influenced athlete monitoring and training program regulation. Meanwhile, session RPE is not prone to data errors from HR measurements and does not require the processing time associated with wearable accelerometer technology. The agreement observed between $sRPE_{TL}$ and hematological metrics suggests that sRPE is an effective alternative to HR metrics during rowing training and provides a cost-effective and time-efficient monitoring strategy.

Conclusion

In conclusion, this study demonstrates a significant correlation between subjective and objective training loads in elite rowers, with ACWR, TM, and TS effectively tracking CK and BU fluctuations. These findings support the integration of subjective load monitoring with periodic hematological assessments to optimize training adaptation. Given the correlation between objective and subjective load monitoring indicators, coaches can adjust training schedules based on subjective data during training weeks and combine this with hematological tests to further promote positive adaptations. Future research should employ longitudinal, minimally invasive approaches to establish dose-response relationships and identify optimal monitoring strategies across training phases.

Acknowledgments

The experiments comply with the current laws of the country where they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who organized the study.

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Key points

- The sixth week was an adjustment phase aimed at reducing the training load, but sRPE remained high, suggesting that rowers had accumulated fatigue from previous weeks of training.
- In elite rowers, moderate to large correlations were observed between subjective and objective training loads during a 6-week training microcycle.
- The relationship between CK and ACWR suggests that the mechanism by which ACWR predicts injury may involve creatine kinase concentration and poor load tolerance.
- These findings suggest that $sRPE_{TL}$ and its derivative indicators can be integrated into the daily routines of elite rowing teams, helping coaches, sports scientists, and practitioners better prepare athletes for competitions.

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