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Human Kinetics
ORIGINAL INVESTIGATION

Resistance Training Affects Neuromuscular Fatigue But Not Efficiency in Elite Rowers

Timo B. van den Bogaard, Jabik-Jan Bastiaans, and Mathijs J. Hofmijster

Purpose: To investigate how resistance training (RT) in a regular training program affects neuromuscular fatigue (NMF) and gross efficiency (EGROSS) in elite rowers. ***Methods:*** Twenty-six elite male rowers performed 4 RT sessions within 10 days. At baseline and after the first and fourth RT, EGROSS and NMF were established. From breathing gas, EGROSS was determined during submaximal rowing tests. Using a countermovement jump test, NMF was assessed by jump height, flight time, flight-to-contraction-time ratio, peak power, and time to peak power. Muscle soreness was assessed using a 10-cm-long visual analog scale. ***Results:*** No significant differences were found for EGROSS ($P = .565$, $\omega^2 = .032$). Muscle soreness ($P = .00$, $\omega^2 = .500$) and time to peak power ($P = .08$, $\omega^2 = 0.238$) were higher compared with baseline at all test moments. Flight-to-contraction-time ratio, jump height, and peak power after the fourth RT differed from baseline ($P < .05$, $\omega^2 = .36$, $\omega^2 = .38$, and $\omega^2 = .31$) and from results obtained after the first RT ($P < .05$, $\omega^2 = .36$, $\omega^2 = .47$, and $\omega^2 = .22$). ***Conclusions:*** RT in general does not influence EGROSS, but large individual differences (4.1%–14.8%) were observed. NMF is affected by RT, particularly after multiple sessions. During periods of intensified RT, imposed external load for low-intensity endurance training need not be altered, but rowers are recommended to abstain from intensive endurance training. Individual monitoring is strongly recommended.

Keywords: rowing, elite performance, concurrent training, movement economy, oxygen consumption

Rowing performance is strongly related to strength and muscle mass.[1,2] To improve muscle strength and maximal power output, resistance training (RT) is adopted by many competitive rowers. RT has been shown to lead to improved neuromuscular capacity, hypertrophy, vascular proliferation, and increased anaerobic energy supply.[3,4]

Despite these favorable long-term effects of RT on rowing performance, acute neuromuscular fatigue (NMF) following even a single bout of RT may potentially interfere with training effects of subsequent training sessions,[5] irrespective of training background, and especially when there is insufficient recovery time.[6,7] It is well established that NMF decreases muscle force generating capacity in mainly type II muscle fibers, which in turn impairs performance during high-intensity activities for athletes both inexperienced and experienced with RT.[3,6,8–10] In addition, there is a growing body of evidence suggesting that NMF negatively interferes with the execution of submaximal intensity endurance training sessions in the day(s) following a RT session.[6,7]

Reductions in running economy as well as cycling gross efficiency (EGROSS) have been shown following RT.[7,11] Such reductions would affect both maximal as well as submaximal performance, as they result in an increased physiological cost of exercise during subsequent endurance workouts. When an external training load is imposed (eg, maintain a certain power output), as is often the case in competitive sports, this, in combination with a reduced EGROSS, could either lead to underloading (early cessation of the workout because the athlete cannot maintain the effort) or overloading (athlete maintaining the imposed external target, resulting in a higher than intended internal load). Repetitively underloading or overloading may, respectively, lead to RT-induced suboptimal endurance development or overtraining.[7]

While several studies have reported that RT perturbs the economy of movement during submaximal running and cycling protocols, few studies have investigated the acute effects of RT in high-performance rowing. Gee et al[8,9,12] found 2000-m rowing ergometer performance to be unaffected following either one bout of RT or following a week containing 3 similar RT sessions, even though NMF was present in both cases. To what extent EGROSS was attenuated was not investigated in these studies. As argued above, reductions in EGROSS can have important implications for submaximal performance as well as exercise prescription. To the best of our knowledge, no research is available on the effect of RT on EGROSS in rowing.

In this study, we investigated the acute effects of RT on the execution of subsequent endurance training sessions in a group of elite rowers. To that aim, we assessed how movement execution and movement economy (quantified as EGROSS) were affected in a submaximal task during a 10-day period containing 4 RT sessions. In addition, we assessed the effect of RT on NMF and muscle soreness in this elite group, and investigated whether changes in NMF could be related to changes in EGROSS.

Methods

Participants

Twenty-six elite male rowers (aged 26.5 [3.5] y, body weight: 95.2 [6.7] kg) were recruited in this study. All rowers participated at international competitions, including world cups, world championships, and Olympic Games, and had at least 1-year experience with RT. All rowers belonged to the same training group. Based on training frequency and training hours, all participants were classified as performance level 5 athletes.[13] All participants provided

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written informed consent. The study was in accordance with the ethical guidelines of the Faculty of Behaviour and Movement Sciences, Vrije Universiteit Amsterdam, and the Declaration of Helsinki.

Research Design

The study was setup as a within-participant repeated-measures design. All measurements were performed within a 10-day period in November, during the "preseason" (ie, period preceding the competitive season). This phase is characterized by a higher than average frequency of high-intensity RT sessions. All participants were instructed to abstain from strenuous exercise, particularly RT, in the week prior to the study.

All participants performed their regular training program, consisting of 4 RT sessions and a moderate volume of low-intensity endurance training. Each RT session consisted of a warm-up followed by 7 multijoint exercises aimed at both upper (eg, bench press and barbell row) and lower body (eg, squat and deadlift) strength. Repetitions ranged between 4 and 8, with 3 to 5 sets per exercise, with the lifted weights in accordance to previously established 6 to 12 repetition maximum. The RT program was designed by the national federation's strength and conditioning trainer. A full description of the prescribed training sessions as well as details of the RT protocol are provided in Table 1.

Baseline values were established prior to the first RT on day 1 (EGROSS) and day 2 (NMF) of the 10-day monitoring period. EGROSS was obtained using a submaximal test; indicators of NMF were established using a countermovement jump (CMJ) protocol and by obtaining subjective muscle soreness scores. All measurements were repeated after RT1 and RT4. All measurements are described in detail below; Figure 1 provides a schematic overview of the 10-day training period.

To ensure minimal interference with the regular training program and maximum compliance of athletes and coaching staff, all measurements were performed at the national training facility.

Test Procedures

Each submaximal test was performed on a rowing ergometer (RP3; RowPerfect, Haaksbergen, the Netherlands) and consisted of four 4-minute stages at incremental power output at a prescribed stroke rate, with 1-minute (after stages 1 and 3) or 1½-minutes (after stage

Table 1 RT Program During the Study

Description of exercise	Sets × repetitions	RM
Resistance training 1		
Warm-up: foam roller and aqua bag squat and side woodchopper	2×6	—
Romanian deadlift	5×5	9
Dumbbell walking lunges	3×6	10
Weighted pull-up	4×5	9
Incline chest press	3×6	10
Superset: single-leg squat/Valslide saws/low to high chop	3×8	—
Resistance training 2		
Warm-up: dead bugs, stick prayer stretch, aqua bag snatch, miniband side steps + squats	2×8	—
Front squat	5×5	6
Barbell single-leg Romanian deadlift	3×5	9
Dumbbell single-arm row	4×5	9
Dumbbell standing single-arm shoulder press	3×6	10
Superset: Roman chair static hold with dumbbell row/diamond push-ups/dumbbell cross-body chop	3×6	—
Resistance training 3		
Warm-up: foam roller bird dog, inchworm, Swiss ball "stir the pot," aqua bag walking lunges	2×6	—
Barbell Bulgarian split squat	5×5	6
Dumbbell single-leg hip thrusters	3×6	10
Barbell bent-over row	4×5	9
Dumbbell chest press	3×6	6
Lat pull-down	3×8	12
Swiss ball saw	3×7	—
Aquabag backward lunge with rotation	3×4	—
Resistance training 4		
Warm-up: foam roller and aqua bag squat and side woodchopper	2×8	—
Romanian deadlift	5×5	8
Dumbbell walking lunges	3×5	8
Weighted pull-up	4×5	8
Incline chest press	3×6	9
Superset: single-leg squat/Valslide saws/low to high chop	3×6	—

Abbreviation: RM, repetition maximum.

2) rest between stages. All participants were familiar with the test protocol, as the test was a shortened version of a frequently performed periodic performance assessment test. Details of the test can be found in Table 2. Both power output and stroke rate were chosen in consultation with the coach.

Throughout the test, breath-by-breath gas exchange was analyzed (Quark CPET; COSMED, Rome, Italy). Metabolic power production was calculated from oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using the method described by Garby and Astrup.[14] Mechanical power output was calculated by the RP3 computer from flywheel kinematics. Reliable and valid power output measures were previously reported using nearly identical methods during similar steady-state rowing protocols with Concept 2 rowing ergometers.[15,16] Stroke length (in meters) and stroke rate (in strokes per minute) were used as indicators of movement execution and were provided by the RP3 computer. Stroke length was defined as the distance between minimal and maximal handle distance to the flywheel for each stroke cycle. Details about workings of the RP3 computer were obtained from personal communication with the manufacturer.

The EGROSS was defined as the ratio between mechanical and metabolic power production.[17] EGROSS was calculated as the average ratio for the last 2 minutes of each stage. To prevent overestimation of EGROSS due to an (unmeasured) anaerobic contribution to the total metabolism, values of EGROSS were discarded when respiratory exchange ratio (RER) exceeded 1.00.[17] Directly following each test, each participant was asked to rate his perceived exertion on a 0 to 10 scale.[18]

In addition to the endurance testing, each participant performed a series of 3 CMJs. Jumps were performed on days 2, 3, and 10 (Figure 1), and always executed before the first training of the day. Prior to the CMJ tests, participants indicated their perceived muscle soreness score on a 10-cm visual analogue scale, ranging from "no pain/ soreness" (0) to "pain/ soreness as bad as it could be" (10). Scores were obtained using a standard ruler, with an accuracy of 1 mm. This scale has been shown to be a valid measure for muscle soreness[6] and was applied in research on rowing performance before.[8,9,12]

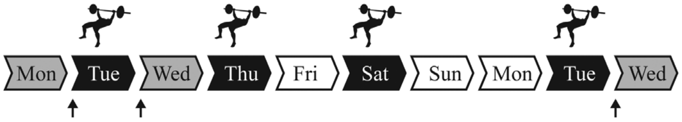

Figure 1 — The 10-day monitoring period. Black-colored days indicate a day with resistance training; gross efficiency was determined at the gray-shaded days. Vertical arrows indicate that CMJs were performed to establish neuromuscular fatigue. Muscle-soreness scores were always obtained just before the CMJs. CMJs indicate countermovement jumps.

Table 2 The Standardized Submaximal Test Used to Establish Gross Efficiency

	Stage 1	Stage 2	Stage 3	Stage 4
Rest after stage, min	1	1.5	1	–
Stroke rate, min^{-1}	18–22	20–24	22–26	24–28
Intensity, W	220	260	280/300/320[a]	330/350/370[a]

Note: The table shows the rest between stages, the range stroke rate was supposed to fall within, and the prescribed intensity for each stage.

[a] Prescribed power output depended on body mass. Values are for body mass up to 90 kg, between 90 and 100 kg, and in excess of 100 kg, respectively.

Each CMJ commenced from an upright standing position (the reference position), after which the participant descended to his perceived optimal depth and explosively ascended to jump to maximal height. Participants were holding a lightweight wooden stick (approximately 0.3 kg) at their upper back (ie, the M. trapezius pars descendens) and were instructed to hold the stick horizontal and have it keep touching their back during the jump, until landing. After landing, the investigator counted down from 5 to 0 and the jump was repeated until 3 acceptable jumps were performed. A jump was considered acceptable when forward and lateral displacement were negligible, and the stick was kept horizontal while touching the neck during the entire jump sequence.

The stick was attached to a linear position transducer at one end (GymAware; Kinetic Performance Technology, Canberra, Australia), which provided data on (vertical) position change in time of the wooden stick. From each jump, jump height (in meter), flight time (in seconds), flight-to-contraction time ratio (F:C), peak power (PP, in Watts), and time to PP (in seconds) were obtained by the GymAware system. Earlier research indicated that these outcome variables are valid indicators of NMF.[19,20] For each CMJ outcome variable, the average of the 3 CMJs was taken.

Jump height was defined as the difference between maximum height of the stick in the air and the height of the stick in the reference position. Flight time was defined as the time difference between leaving the ground (stick passed through reference position in the upward motion) and landing (stick passed through the reference position in the downward motion). The F:C ratio was defined as the ratio between flight time and contraction time, with contraction time being the time it took the stick to get from the lowest position through the reference position. PP was defined as the highest positive work rate throughout the CMJ, with work rate calculated as the rate of change of potential energy would the participants mass be situated at the point where the linear positional transducer was attached to the wooden stick. Time to PP was defined as the time difference between the lowest position and PP.

Statistical Analysis

Before statistical analysis, data were checked for normality using the Kolmogorov–Smirnov test, and for homogeneity of variance using the Levene test. Differences in EGROSS, stroke length, and stroke rate were assessed using a 3 × 4 (test number × stage number) repeated-measures analysis of variance. Effect sizes were reported as omega squared (ω^2) as for small sample sizes this is a less biased measure compared with eta squared.[21] Omega squared can be interpreted as the amount of variance in the dependent variable that can be attributed to RT.[22] Differences in CMJ variables, rating of perceived exertion, and perceived muscle soreness scores were assessed using 3 × 1 repeated-measures analysis of variance. Assumption of sphericity was assessed using Mauchly test, and when violated, Greenhouse–Geisser correction was performed. When a significant main effect was found, post hoc pairwise *t* tests were performed. To assess whether EGROSS was related to NMF, Pearson *r* was calculated between EGROSS and CMJ performance outcomes as well as muscle soreness scores. For each analysis, the level of significance was set to $P < .05$. Statistical analyses were performed using IBM SPSS statistics (version 25; SPSS Inc, Chicago, IL).

Results

Effect of RT on EGROSS and Movement Execution

A total of 15 participants provided comprehensive EGROSS data (ie, completed all submaximal endurance tests and had an RER ≤1.00 during all stages of the test). As the assumption of sphericity was violated, degrees of freedom were adjusted according to Greenhouse–Geisser (test number $\varepsilon = .701$, stage number $\varepsilon = .451$, interaction $\varepsilon = .454$). A significant main effect was found for stage number: $F_{1.352,18.934} = 59.960$, $P = .000$, $\omega^2 = .811$. Post hoc test revealed EGROSS to increase with increasing stage number ($P = .000$) indicating that EGROSS increased at increasing intensities. EGROSS did not differ between test numbers: $F_{1.401,19.624} = .469$, $P = .565$, $\omega^2 = .032$. No interaction effect was found $F_{2.726,38.171} = .831$, $P = .549$, $\omega^2 = .056$. EGROSS across different tests and stages are provided in Figure 2. These findings suggest that, for this group of elite rowers, RT does not influence EGROSS. In addition, rating of perceived exertion ($P = .176$), stroke rate ($P = .198$), and stroke length ($P = .540$) did not differ significantly between test moments. Table 3 provides an overview of the test statistics.

Effect of RT on Indicators of NMF

A total of 18 participants completed all the CMJ tests, while 24 participants provided perceived muscle soreness scores on all occasions. All NMF indicators (ie, jump height, flight time, F:C ratio, PP, TuPP) were normally distributed according to the Kolmogorov–Smirnov test. Mauchly test indicated that the assumption of sphericity was met for all variables. A significant main effect was observed for all NMF-related variables across test moments.

Post hoc tests revealed that perceived muscle soreness ($P = .000$) and time until PP scores ($P = .008$) were significantly higher compared with baseline at all test moments. The F:C ratio, jump height, and PP did not differ significantly from baseline after RT1. However, after RT4, these variables were significantly lower compared with baseline and RT1. This indicates that muscle soreness was increased throughout the entire RT period, while CMJ performance was mostly unaffected after 1 RT session but decreased significantly as the RT period progressed. Effect sizes are considered small ($0.2 < \omega^2 < .05$). See Table 3 for a complete overview of the test statistics. Figure 3 shows the change in CMJ performance as well as the change in muscle soreness scores compared with baseline across all test moments.

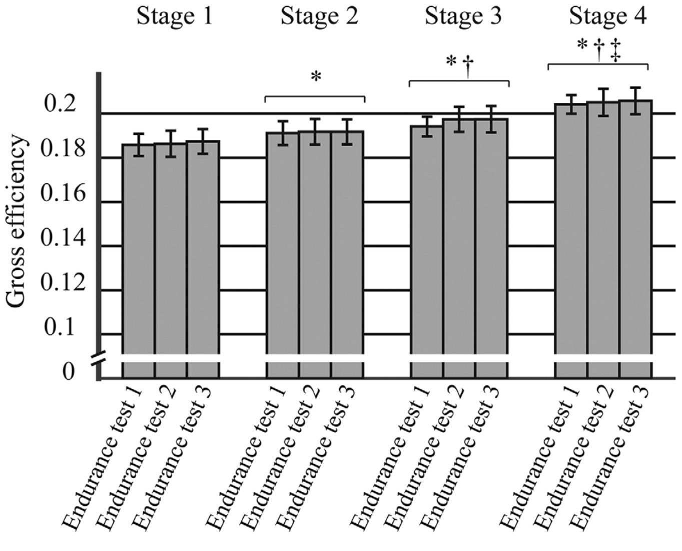

Figure 2 — Gross efficiency obtained during the 3 stages of the 3 endurance tests. Error bars indicate the CIs for each condition. No differences where observed between tests within the same stage. No significant interaction between stage and test was found. Note that CIs are plotted to provide an indication of the variability between participants within each condition. They do not influence statistics of within-participant comparisons. *Significantly different from stage 1. †Significantly different from stage 2. ‡Significantly different from stage 3 ($P < .05$ for all differences). CI indicate confident interval.

Relation Between EGROSS and NMF

No significant correlations were found between EGROSS and any of the CMJ outcome values or muscle soreness scores ($P > .05$ for all comparisons). This indicates that in this group of elite rowers, EGROSS is unrelated to factors associated with NMF.

Table 3 Overview of Test Statistics Concerning Outcome Variables Associated With Movement Execution and Neuromuscular Fatigue

	n	Test statistic	*P*	ω^2
RPE	15	$F_{2,36} = 1.826$	.176	.183
Stroke rate	15	$F_{2,42} = 1.682$	.198	.074
Stroke length	15	$F_{2,42} = .625$	.540	.183
F:C ratio	18	$F_{2,34} = 6.076$	.005	.252
Jump height	18	$F_{2,34} = 4.528$	.018	.210
PP	18	$F_{2,34} = 8.429$	.001	.331
TuPP	18	$F_{2,34} = 5.619$	.008	.238
Muscle soreness	24	$F_{2,46} = 23.012$	.000	.500

Abbreviations: F:C, flight-time-to-contraction-time ratio; n, number of participants; PP, peak power; RPE, rating of perceived exertion; TuPP, time until PP; ω^2, effect size.

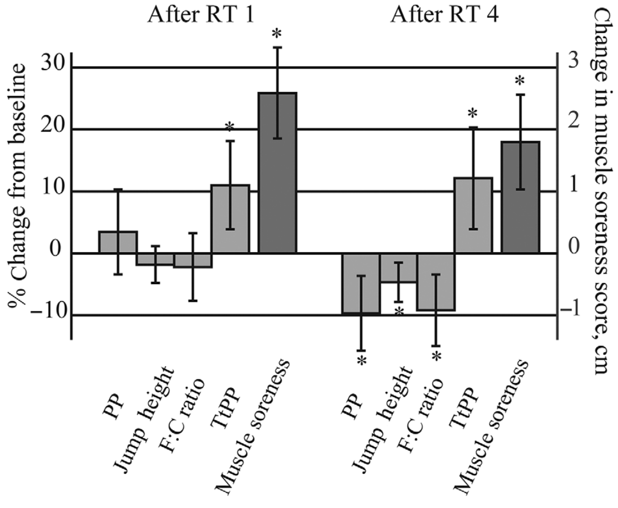

Figure 3 — Relative changes in variables indicative for neuromuscular fatigue (PP, jump height, F:C ratio, and TtPP), as well as absolute change in muscle-soreness scores after RT1 and after RT4, compared with baseline. All significant differences indicate a decrease in performance following RT. Error bars represent the confidence interval of the difference with baseline. F:C ratio indicates flight-to-contraction ratio; PP, peak power; RT, resistance training; TtPP: time to PP. *Significantly different from baseline ($P < .05$).

Discussion

In this study, we found neuromuscular performance in elite rowers likely to be attenuated by RT. Several indicators of NMF were negatively affected after a period of RT, and effects were more pronounced after multiple consecutive RT sessions within the observation period compared with after the first RT. Rowers also reported an increase in muscle soreness after RT. Nevertheless, and contrary to our expectations, EGROSS on average was unaffected.

This finding could possibly be explained by selective muscle fiber damage: it is generally accepted that RT training mainly affects high-threshold type II muscle fibers,[6] which are suggested to only be recruited when force exceeds about 87% of maximum voluntary contraction.[23] For CMJ performance, it is likely that the potentially damaged high-thresholds fibers were recruited during the jump, thereby decreasing jump performance.[8] However, these higher threshold fibers may not have been recruited to a similar extent during the lower stages of the submaximal test, as muscle force production was likely to be well below the aforementioned 87% of maximal voluntary contraction. This could explain EGROSS to be unperturbed at submaximal intensities. Furthermore, Gee et al[8] hypothesize from an increase in central motor drive during a 2000-m time-trial after several RT sessions that activation patterns are altered, which might imply that undamaged type I fibers are recruited to compensate affected type II fibers. This argument is supported by findings of Doma et al,[24] who found oxygen cost of submaximal running to be unaffected while maximal running performance was attenuated during a 6-day period of combining RT with high-intensity endurance training. In addition, So et al[25] found elite rowers to be more effective than novices in alternating muscle activation patterns to prevent muscle fatigue. The authors suggested that this alternation in muscle recruitment strategy may be beneficial for maintaining power output while fatigued. As using a relatively high percentage of type I fibers is associated with higher EGROSS,[7,26] this could be an alternative explanation why on average EGROSS in our group was not attenuated. As we did not obtain EMG, we cannot confirm this hypothesis. Clearly, this is a topic for future research.

Contrary to our results, it is well established that running economy is impaired as a consequence of RT.[7] The authors suggest this to be a result of altered movement kinematics, which in turn are caused by NMF. Compared with running, the degrees of freedom in rowing are limited; rowers are more restricted in their possibilities to alter movement kinematics when muscles are fatigued or sore compared with runners,[7] which possibly limits the effect on EGROSS. The fact that we did find indications of NMF in the absence of a change in movement kinematics supports this argument.

The RT-induced changes in EGROSS were reported for cycling,[11] when EGROSS was obtained 3 hours after RT. Attenuated (submaximal) force production caused by a reduction in calcium release from the sarcoplasmic reticulum has been reported to be an acute effect of RT[6] and has been suggested to negatively affect EGROSS.[27] This effect diminishes in a matter of hours[28] and is a potential explanation for the difference between our findings and the findings of Deakin.[11] While we were specifically interested in the effects of RT in the days following RT, it remains to be investigated whether EGROSS in rowing is attenuated directly following RT.

A third explanation of the discrepancy of our results compared with earlier findings showing decreased movement economy in runners is provided by Gee et al,[8] who suggest that rowers show greater "physical robustness" compared with other endurance athletes. Indeed, all participants in our study were of elite level and had considerable experience with RT. This potentially leads to what has been referred to before as the "repeated bout effect"[29]; that is, improved resilience to the acute negative effects of RT like muscle damage due to experience with the loaded eccentric exercise during RT.

While on average, EGROSS appeared to be unaffected, our results show that individual results differ substantially. Unfortunately, we were unable to ascertain whether the differences in individual responses were robust, or the result of equipment noise and/or day-to-day intraindividual biological variations. Indeed earlier studies pointed out that training responses in athletes show high interindividual variability.[30] Obviously, this would have large implications for individualized training programs for athletes combining strength and endurance training. Of particular notice is that in our group of participants, relative changes in EGROSS from baseline to the third test ranged between −4.1% and +14.8%. This is well above the smallest detectable difference, which was reported to be ±3.2%, based on the day-to-day variation in EGROSS[31]—much smaller than the changes found for some participants in our group. This suggests that EGROSS in some individuals indeed was affected (both positively and negatively) by RT. Future research should therefore be focused both on individual effects of RT, as well as on whether individual differences in responses of RT can be explained by physiological characteristics.

Practical Applications

Periods where intensive RT is combined with low-intensity training sessions are common rowing practice.[3] While in such periods, the focus is on strength progression, prescribing the correct intensity for concurrent endurance training sessions is key to prevent overtraining or undertraining. As endurance training in rowing is often prescribed by external load measures (eg, mechanical power or pace), EGROSS directly affects the associated experienced internal load. Our results imply that in general coaches should not have to alter prescribed external load for endurance training sessions in a period with multiple bouts of intensive RT, especially when the imposed training load for those sessions is relatively low, but that they should consider the fact that some individuals might be negatively affected. This obviously is notwithstanding the fact that combining strength and endurance training while preventing negative interference between those 2 training modalities poses several other well-established challenges, such as the order in which the 2 modalities should be executed or the period of rest needed between training sessions.[32] Finally, our results indicate that both NMF and perceived muscle soreness is present after RT, which argues against performing high-intensity endurance sessions in the days following RT sessions.

Conclusions

Our results indicate that common RT practices in rowing induce NMF in elite rowers, especially after multiple bouts of RT. However, this has on average no influence on EGROSS during submaximal rowing. Future research should indicate whether the latter still holds at an individual level.

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