ASMFA ADVANCES IN SKELETAL MUSCLE FUNCTION ASSESSMENT

EFFECTS OF ACTIVE RECOVERY ON MUSCLE FUNCTION FOLLOWING HIGH-INTENSITY TRAINING SESSIONS IN ELITE OLYMPIC WEIGHTLIFTERS

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KEY WORDS:

Fatigue;
Performance;
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Muscle damage;
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ABSTRACT

This study investigated whether the repeated use of an active recovery (ACT) program is beneficial for promoting recovery of muscle function during an intensive training phase in elite Olympic weightlifters. Using a crossover design, eight competitive weightlifters (7 male; 1 female) from the German national Olympic team participated in a two-day microcycle, comprising of four high-intensity training sessions, with either ACT or passive recovery (PAS) following the session. Barbell velocity during the clean pull, countermovement jump (CMJ) height, muscle contractile properties using tensiomyography (TMG), creatine kinase activity (CK), muscle soreness (DOMS) and perceived overall recovery and stress were measured. After termination of the microcycle, the sport-specific performance during all clean pull intensities (85% 1RM, ACT: Effect size (ES) = -0.20, PAS: ES = -0.50; 90% 1RM, ACT: ES = -0.29, PAS: ES = -0.35; 95% 1RM, ACT: ES = -0.41, PAS: ES = -020; $P > 0.05$) decreased. Both CK (ACT: ES = 2.11, PAS: ES = 1.41; $P = 0.001$) and DOMS (ACT: ES = 1.65, PAS: ES = 2.33; $P = 0.052$) considerably increased. Similarly, ratings of perceived recovery and stress were adversely affected in ACT and PAS, whereas changes in CMJ height and TMG muscle contractile properties remained trivial in both conditions. No practically meaningful differences in changes of the outcome measures were found between ACT and PAS, however there were variable individual responses to ACT. In conclusion, the short-term implementation of an individualized ACT program does not seem to enhance recovery from training-induced fatigue more effectively than PAS. However, because of the inter-individual variability in responses to ACT, it may be beneficial at the individual level.

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INTRODUCTION

Weightlifting is a dynamic strength and power sport comprising two competitive lifts, the snatch and the clean and jerk, which require the athlete to develop very high peak forces and contractile rates of force development. [1]. Therefore, the training plan of competitive weightlifters includes multiple daily high-intensity training sessions, 5-7 days per week, of the same major muscle groups and similar multi-joint movement exercises as in the competitive lifts.[1-3]. Such frequent exposure to strenuous high-resistance training loads in close density places high demands on their recovery abilities in terms of a rapid performance restoration after intense training sessions [4, 5]. Insufficient recovery may adversely affect the capability to cope with the demands of the training volume and intensity during the subsequent training sessions [5]. Therefore, optimizing post-training recovery during intense training periods may effectively reduce the fatigue incurred from training or decrease the severity of fatigue symptoms. [6]. This may also allow the athlete to tolerate higher training loads with respect to frequency, volume and intensity and to increase the impact of a given training stimulus [5].

Active recovery (ACT) is a commonly used method by athletes immediately after training or competition to promote the recovery mechanisms at the muscular and psychological level, and thus restore performance more quickly [7, 8]. ACT strategies usually include low-to-moderate intensity aerobic-type dynamic activities (i.e., swimming, cycling, running) at 30-60% of the individual aerobic capacity or 60-100% of the individual lactate threshold for a minimum duration of 10 to 30 minutes [7, 8]. ACT from intense muscular strain increases muscle perfusion, promotes nutrient transport to damaged tissues, enhances clearance of waste products and elimination of muscle cell debris without causing more muscle damage, as well has a temporary analgesic effect on sore muscles [7, 9, 10]. In addition, post-resistance exercise ACT strategy does not inhibit the acute anabolic response or suppress ribosome biogenesis and subsequent muscle protein synthesis, and also does not affect long-term adaptations in strength and muscle mass [11, 12].

While ACT immediately after a match in rugby players has been reported [13] to significantly speed-up muscle damage recovery (measured by creatine kinase activity) compared to passive recovery (PAS), Suzuki et al revealed no beneficial effect of post-match ACT on reducing muscle damage in collegiate rugby players, although the athletes seemed to benefit from an increased psychological recovery [14]. Furthermore, while ACT improve recovery of isometric leg extensor strength in untrained women 72 hours after an eccentric exercise protocol promoting muscle damage [9], other studies reported no useful effects of post-competition ACT on the rate and magnitude of alterations in neuromuscular performance as well as on biochemical and perceptual changes in elite female soccer players [15], male futsal players [16] and male football players [17]. Therefore, the current evidence is conflicting, with a lack of studies on elite strength-power athletes investigating ACT as potentially effective recovery method. Moreover, previous studies have primarily examined effects of ACT on recovery after a single training session. The effect of repeated use of ACT during intense training periods is yet to be investigated. Therefore, the present study aimed to investigate the short-term effectiveness of repeated ACT compared with PAS during a 2-day high-intensity training microcycle on sport-specific performance as well as on neuromuscular, biochemical and perceptual markers of fatigue in elite Olympic weightlifters. We hypothesized, first, that the training program would induce an acute decrease in physical performance as well as adverse effects in several markers of fatigue. Our second hypothesis was that the application of ACT would accelerate recovery more effectively than PAS during the training period and thus would decrease the magnitude of training-induced fatigue.

METHODS

Experimental design

A cross-over study design was used to investigate the effects of repeated ACT compared to PAS on the recovery pattern of sport-specific performance and several markers of fatigue (**Figure 1**). Participants completed two similar training microcycles separated by a two-week wash-out period in order to control training progress. The two training periods were embedded inside short consecutive "heavy load weeks" to ensure the induction of fatigue. Inside the first microcycle (MC 1), the participants were allocated to either an ACT or PAS intervention, matched on competition performance. In the second microcycle (MC 2), the participants changed the recovery modalities.

Sport-specific performance comprising maximal barbell velocity during the clean pull (CP), as well as markers of fatigue including countermovement jump (CMJ) performance, TMG muscle contractile properties (maximal muscle belly displacement, Dm; muscle contraction velocity, V90), muscle damage (serum creatine kinase activity, CK), muscle soreness (Delayed Onset Muscle Soreness, DOMS), and perceived stress and recovery levels (using the novel Short Recovery and Stress Scale, SRSS [25]) were collected one day before (Pre) and one day after (Post) completing the microcycles. These consisted of four training sessions, morning (9.30 – 11 am) and afternoon (3.30 – 5 pm), organized over two training days (**Figure 1**). Immediately after each training session, the participants performed either ACT (submaximal rowing ergometer exercise) or PAS (resting in a seated position) for 15 minutes. In addition, CMJ and SRSS were also measured before (pre T2, pre T3, and pre T4) and after the training sessions (post T1, post T2, post T3, and post T4) as well as after ACT or PAS (post R1, post R2, post R3 and post R4).

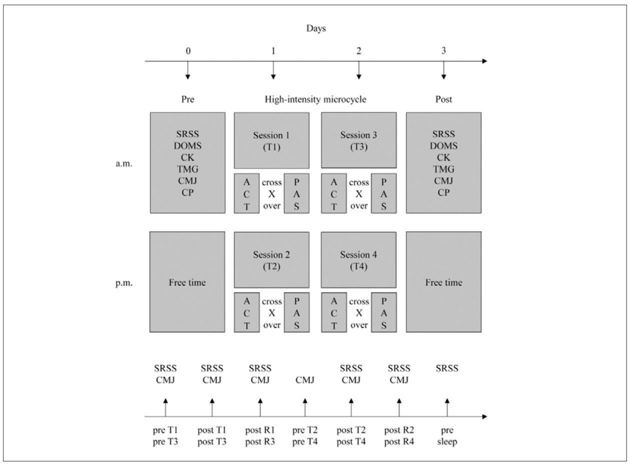

Figure 1. Schematic representation of the study design.
SRSS, Short Recovery and Stress Scale; DOMS, Delayed Onset Muscle Soreness; CK, serum Creatine Kinase; TMG, Tensiomyography, CMJ, Countermovement Jump, CP, Clean Pull; ACT, Active recovery; PAS, Passive recovery; T, Training session, R, Recovery intervention.

MEASUREMENTS

Sport-specific performance: The CPs were performed in a fixed order at Pre and Post, and were used to measure maximal barbell velocity corresponding to 85% (CP85), 90% (CP90) and 95% (CP95) of the maximum load (i.e., 1RM). During CPs, participants vertically lifted the barbell (using a shoulder-width grip) in one continuous movement with the goal to maximize barbell velocity **[1]**. The barbell was aggressively accelerated by explosively extending the body upward using lower-body triple extension (fully extended hips, legs and ankles) **[18]**. Following the completion of the CP, the barbell was dropped to the floor.

Maximal barbell velocity is an important indicator of sport-specific performance **[19]** and was determined through a special measuring system based on video image analysis using a camcorder (Panasonic GS 500, Panasonic Corporation, Kadoma, Japan) and analogous software package (Realanalyzer, IAT Leipzig, Germany) with the participants standing on a measuring platform. During each attempt, the center of the outer weight plate was set as a point of reference and then digitally tracked by a video camera using a sampling rate of 50 Hz. Thus, the vertical displacement of the barbell could be measured as a function of time and, consequently, the maximal barbell velocity besides a variety of other kinematic variables. Adequately high reliability scores for overall CP [$\text{cm}\cdot\text{s}^{-1}$] were previously found among elite weightlifters, n = 20: Intra-class correlation coefficient (ICC) = 0.717, typical error (TE) = 6.4, coefficient of variation (CV) = 3.4%.

Jump performance: CMJs were performed at Pre and Post and additionally before and after each training session as well as after ACT or PAS using a contact platform (Haynl Elektronik, Schönebeck, Germany). During the CMJ, the participants placed the hands on the hips and squatted down to a self-selected level before jumping for maximal height. Jump height was calculated from the flight time. At each measurement point, the participants performed three CMJs and the mean jump height was taken for later analysis. Reliability scores were previously calculated in our own laboratory and considered highly reliable in CMJ [cm], n = 38: ICC = 0.915, TE = 1.86, CV = 3.7%.

Muscle contractile properties: The TMG was used as a non-invasive and involuntary (independent of central activation) method to determine muscle contractile properties of the lower extremity without inducing additional fatigue **[20]**. TMG measurements were conducted at Pre and Post using a electrical stimulator (TMG-S2), analogous TMG-OK 3.0 software, as well as a spring-loaded displacement sensor tip (TMG-BMC, Ljubljana, Slovenia) with a prefixed tension of 0.17 N m-1 positioned on the centre point of the belly of the vastus medialis muscle **[20]**. The sensor location was carefully determined before the first TMG measurement for each individual participant. The muscular geography of the vastus medialis is generally well displayed, especially in weightlifters. While the participants were asked to perform a voluntary knee extension, the centre point of the muscle belly could thus be estimated relatively accurately, taking into account the specific fiber orientation (i.e., vastus medialis muscle fibres run at ~ 55° angle medial to the tendon of quadriceps muscle). This position was considered to be the point of maximal muscle belly displacement. The measuring point was then marked with a dermatological pen and was kept constant during the study period. The self-adhesive electrodes were placed symmetrically approximately 5 cm away from the sensor. TMG measurements were performed in a supine position and a knee joint angle of 120° was held constant using supporting pads. The TMG muscle contractile properties assessed were Dm (indicator of muscle stiffness or muscle contractile force), and the mean velocity of muscle contraction from the onset of electrical stimulation until 90% of Dm (V90) **[20, 21]**.

During squat exercise, an integral component in weightlifting training routines, the activity of vastus medialis and lateralis is greater than of rectus femoris. The vasti muscles equally contribute to muscle force output, and they produce approximately 50% greater muscle force output as the rectus femoris **[22]**. Therefore, the muscle contractile properties of vastus medialis were measured in this study, since we expected a greater responsiveness due to higher mechanical strains. Reliability scores were previously determined in our own laboratory and considered sufficient reliable in Dm [mm], n = 20: ICC = 0.918, TE = 1.0, CV = 9.3% and in V90 [mm · s-1], n = 20: ICC = 0.781, TE = 16, CV = 9.9%.

Muscle damage: Venous blood samples for analysis of serum creatine kinase (CK) activity were used as indirect evidence of muscle damage and taken at Pre and Post (between 8 and 10 am). The blood samples were collected using 7.5 mL serum gel tubes with clotting activator (Sarstedt; Nürnbrecht, Germany). The samples were positioned upright for 20 minutes and subsequently centrifuged at 3500 rpm for 15 minutes. Serum was aliquoted into microtubes (Sarstedt; Nürnbrecht, Germany), frozen at -80°C within 60 minutes after collection, and stored for later analysis. The determination of CK activity was then conducted by routine techniques (UniCell DxC 600 Synchron; Beckmann Coulter GmbH, Krefeld, Germany). Reliability scores were calculated with the present participants and considered sufficient reliable in CK [U · L-1]: ICC = 0.825, TE = 94, CV = 17.3%.

Muscle soreness: DOMS was measured at Pre and Post using a visual analogue scale (VAS). The VAS consists of a 10 cm line with endpoints labeled as "no pain" (left) and "unbearable pain" (right). The participants palpated their lower limbs and made a vertical mark at a point on the line that best represented their current rating of soreness. The score was the distance in cm from the left side of the scale to the point marked **[23]**. A 5-10mm change in pain rating on a 100mm VAS has been considered a small effect of clinical importance **[24]**. To be more conservative we decided to define the 2-fold of the lower limit value as the smallest worthwhile change (SWC, 10mm) in the present study.

Perceived recovery and stress: The subjective rating of perceived recovery and stress was determined at Pre and Post, before and after the training sessions and recovery interventions as well as before bedtime (pre-sleep) using the SRSS **[25]**. The participants provided responses to eight items on a rating scale ranging from "0" (does not apply at all) to "6" (fully applies). Numbers "1" to "5" were undefined and used to delineate the degrees of perceived recovery and stress between the two endpoints of the scale. The items used in this study were "Physical Performance Capability" (PPC), "Overall Recovery" (OR), "Muscular Strain" (MS), and "Overall Stress" (OS). Scores for internal consistencies of the SRSS were previously examined among elite athletes and considered to be sufficient (n = 574; Cronbach´s $\alpha > 0.72$) [25]. Jaeschke and co-workers **[26]** reported a minimum clinical important difference of 0.5 per item on a 7-point Likert scale. As already emphasized, to be more conservative we defined the 2-fold of this value as the SWC (change of 1.0 per item) in the present study.

Recovery intervention: ACT was started within 5 min after each training session with 15 min supervised rowing ergometer (Concept2, Hamburg, Germany) exercise at a submaximal load corresponding to approximately 1 Watt per kg body weight and with a stroke frequency of < 20 per minute. A specific pilot study, previously conducted, confirmed this selected intensity as almost completely aerobic-type exercise with blood lactate values < 2 mmol/l and RPE values ranging between 2 and 3 (easy to moderate) on a CR-10 scale.

Training program: The participants completed a total of 4 training sessions (2 sessions / day) during the two microcycles **(Figure 1)**, each with similar training content and volume. The total training load as well as the mean barbell load is given in Figure 2. Besides the two competitive exercises including the snatch and the clean and jerk and their various derivatives, the participants basically performed high-load back and front squats, clean and snatch pulls as well as overhead and push press exercises.

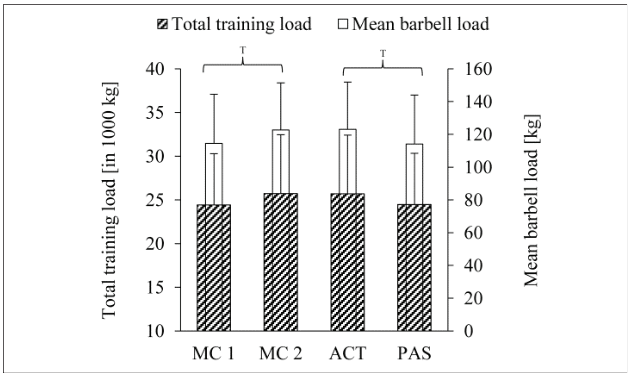

Figure 2. Total training load and mean barbell load in MC 1 and MC 2 as well as in ACT and PAS interventions during the examination period.
MC, Microcycle; ACT, Active recovery; PAS, Passive recovery; T, trivial change in mean.

PARTICIPANTS

Eight competitive male (n = 7) and female (n = 1) elite weightlifters from the German national Olympic team participated in the study **(Table 1)**. They were informed about the experimental procedures and they provided written consent for participation. The study was approved by the local Ethics Committee of the Medical Faculty of the Ruhr-University Bochum and was performed according to the guidelines of the Declaration of Helsinki.

STATISTICAL ANALYSES

Statistical analyses were performed with the IBM SPSS statistical package (version 22; IBM, Chicago, IL, USA). Data are presented as mean ± SD, unless otherwise stated. Assumption of normality was confirmed by means of Shapiro-Wilks-Test before conducting any parametric tests. A repeated-measures analysis of variance (ANOVA) with factors recovery type and time was calculated to determine differences in all analyzed variables between ACT and PAS as well as between the Pre and Post measurement points. Violation of sphericity was adjusted by Greenhouse-Geisser correction. Bonferroni post-hoc comparisons were used if ANOVA main effect was significant. The $p < 0.05$ criterion was used to constitute statistical significance.

In addition, the data were evaluated through analyses of practical relevance using magnitude-based-inferences (MBI), calculated from 90% confidence limits using published spreadsheets (available at www.sportsci.org), in order to assess the probability that the magnitude of differences in the changes between ACT and PAS are practically meaningful **[27]**. The smallest worthwhile change (SWC) was defined as 0.5 of the typical variation in performance (CP and CMJ) as well as in markers of muscle contractile properties (Dm and V90) and muscle damage (CK) **[27, 28]**. In DOMS, the SWC was set as a 10mm change on the VAS **[24]**, whereas in SRSS the SWC was defined as a minimum change of 1.0 per item **[26]**. The between-condition differences in changes of all analyzed parameters were calculated from adjusted pre-values and allocated a qualitative descriptor representing the probability that the true value is of the observed magnitude **[28]**. Qualitative inferences were considered as chances (%) of having a negative (-), trivial, or positive (+) effect, and evaluated as follows: < 0.5%, almost certainly not; 0.5 - 5.0%, very unlikely; > 5.0% - 25.0%, unlikely; > 25.0% - 75.0%, possibly; > 75.0% - 95.0%, likely; > 95.0% - 99.5%, very likely; > 99.5%, most likely **[27]**. If the chance of having a substantially positive or negative effect was both > 5%, the true change was assessed as ‘unclear’. Standardized changes

Table 1. Anthropometric and performance-related characteristics of the participants

						BEST PERFORMANCE		
Subject	Sex	Weight class (kg)	Age (yrs)	Body weight (kg)	Body height (cm)	Snatch (kg)	Clean & Jerk (kg)	Duel (kg)
#1	male	≤ 77	23	78	165	150	190	340
#2	male	≤ 94	29	88	171	156	205	359
#3	male	≤ 105	29	105	176	167	205	370
#4	male	≤ 77	32	81	172	151	183	332
#5	male	≤ 85	22	87	167	145	185	330
#6	male	> 105	26	132	191	185	215	400
#7	male	≤ 105	32	106	175	178	218	391
#8	female	≤ 75	19	74	172	92	112	204
		Mean ± SD	**26.5±4.8**	**93.9±19.3**	**173.6±7.9**	**153.0±28.4**	**189.1±33.8**	**340.8±61.1**

between measurement points and standardized differences in changes between ACT and PAS were also calculated using the effect size (ES), and threshold values of 0.0 – 0.19, 0.20 – 0.59, 0.60 – 1.19, 1.20 – 1.99, and > 2.00 were considered trivial, small, moderate, large, and very large, respectively **[27, 28]**.

RESULTS

There was a significant main effect for time in CK activity and in perceived MS **(Table 2)**, while the other variables remained statistically unaffected **(Table 2 and 3).** Considering the ES statistic, the training microcycle induced large to very large increases between Pre and Post in markers of muscle damage (CK, ACT: ES=2.11, PAS: ES=1.41) and muscle soreness (DOMS, ACT: ES = 1.65, PAS: ES = 2.33) in the two recovery groups **(Table 2)**. There were moderate to large Pre-Post effects in markers of perceived recovery and stress, showing a decrease in PPC (ACT: ES = -0.66, PAS: -1.20) and OR (ACT: ES = -1.35, PAS: ES = -1.33) as well as an increase in MS (ACT: ES = 1.33, PAS: ES = 0.95) and OS (ACT: ES = 1.35, PAS: ES = 1.01) in both recovery groups **(Table 2)**. Furthermore, the training period caused small decreases between Pre and Post in sport-specific performance (CP85, ACT: ES = -0.20, PAS: ES = -0.50; CP90, ACT: ES = -0.29, PAS: ES = -0.35; CP95, ACT: ES = -0.41, PAS: ES = -0.20) as well as trivial Pre-Post changes in markers of jump performance (CMJ, ACT: ES = -0.06, PAS: ES = 0.15) and muscle contractile properties (Dm, ACT: ES = 0.14, PAS: ES = -0.09; V90, ACT: ES = -0.10, PAS: ES = -0.20) in both recovery conditions **(Table 3)**. Moreover, there was no significant recovery type × time interaction between Pre and Post in all the analyzed variables. In addition, magnitude-based inferences revealed no beneficial or detrimental effects of ACT reflected by no meaningful differences in Pre-Post changes between ACT and PAS, both in sport-specific performance and in markers of fatigue **(Tables 2 and 3)**.

A more detailed presentation of neuromuscular performance (CMJ) and selected markers of perceived recovery and stress (PPC and MS) before and after the training and recovery sessions during the entire training period are shown in **Figs 3-5.** Overall, the total mean change from baseline in CMJ was -1.9 ± 5.1 % in ACT and 1.8 ± 4.2 % in PAS; however, the difference in total changes between ACT and PAS was not significant and was deemed practically "unclear". More precisely, ACT induced a likely decreased jump performance immediately post R2 and post R3, while this was not apparent following PAS. Our data further showed that CMJ height very likely differed between the two recovery conditions at post R2 in favor of PAS. These findings are also supported by the observed changes in markers of perceived recovery (PPC) and

Table 2. Markers of muscle damage and muscle soreness as well as perceived recovery and stress at Pre and Post, the absolute mean changes between Pre and Post, and the differences in the absolute mean changes between the recovery modes.

								Group changes				Differences in group changes^a				
Variable	Mode	Pre			Post			Time	ΔPost - Pre			Group x Time Interaction	ΔACT – PAS			Qualitative inference
		Mean	±	SD	Mean	±	SD	P	Mean	±	SD	P	Mean	±	90% CL	
Muscle damage & muscle soreness																
CK [U · L^{-1}]	ACT	254	±	106	558	±	215*	0.001	300	±	149^D	0.816	-25	±	146^A	Unclear
	PAS	241	±	91	562	±	234*		324	±	203^D					
DOMS [mm]	ACT	10	±	9	23	±	18	0.052	13	±	13^C	0.536	-5	±	17^B	Unclear
	PAS	11	±	7	29	±	28		19	±	30^D					
Perceived recovery and stress																
PPC [0-6]	ACT	4.8	±	0.9	4.1	±	1.1	0.225	-0.6	±	1.0^B	0.999	0.5	±	0.7^A	Likely trivial
	PAS	4.3	±	0.7	3.6	±	1.5		-1.0	±	1.6^C					
OR [0-6]	ACT	4.6	±	0.6	3.5	±	0.8	0.069	-1.0	±	0.7^C	0.492	0.0	±	0.6^T	Very likely trivial
	PAS	4.3	±	0.8	3.5	±	1.4		-1.0	±	1.5^C					
MS [0-6]	ACT	1.4	±	1.2	2.9	±	1.0*	0.015	1.4	±	1.0^C	0.434	0.4	±	1.1^A	Likely trivial
	PAS	1.6	±	0.9	2.5	±	1.3		1.0	±	1.4^B					
OS [0-6]	ACT	0.9	±	0.6	2.3	±	1.2	0.084	1.4	±	1.0^C	0.379	0.4	±	1.1^A	Likely trivial
	PAS	1.4	±	1.2	2.1	±	1.7		1.1	±	1.8^B					

ACT, Active recovery; PAS, Passive recovery; CK, serum Creatine Kinase; DOMS, Delayed Onset Muscle Soreness; PPC, Physical Performance Capability; OR, Overall Recovery; MS, Muscular Strain; OS, Overall Stress.

^{a}calculated from adjusted pre-values; *significantly different from Pre; **A** Indicates small effect size (ES = 0.20 - 0.59); **B** Indicates moderate effect size (ES = 0.60 – 1.19); **C** Indicates large effect size (ES = 1.20 - 1.99); **D** Indicates very large effect size (ES > 1.20); **T** Indicates trivial effect size (0.00 – 0.19).

Table 3. Sport-specific performance, jump performance, and muscle contractile properties at Pre and Post, the percentage mean changes between Pre and Post, and the differences in the percentage mean changes between the recovery modes.

								Group changes				Differences in group changes[a]				
Variable	Mode	Pre			Post			Time	%ΔPost - Pre			Group x Time Interaction	%ΔACT – PAS			Qualitative inference
		Mean	±	SD	Mean	±	SD	P	Mean	±	SD	P	Mean	±	90% CL	
Sport-specific performance																
CP85 [cm · s^{-1}]	ACT	165	±	11	163	±	13	0.154	-1.6	±	5.1^{A}	0.363	2.8	±	5.4^{A}	Unclear
	PAS	165	±	16	159	±	21		-4.2	±	5.8^{A}					
CP90 [cm · s^{-1}]	ACT	157	±	12	152	±	16	0.128	-3.2	±	5.8^{A}	0.825	0.6	±	6.9^{T}	Unclear
	PAS	152	±	18	147	±	24		-3.7	±	7.1^{A}					
CP95 [cm · s^{-1}]	ACT	148	±	10	143	±	16	0.057	-4.9	±	6.8^{A}	0.630	-2.6	±	6.4^{A}	Unclear
	PAS	143	±	20	139	±	20		-2.4	±	2.2^{A}					
Jump performance																
CMJ [cm]	ACT	46.6	±	6.5	46.1	±	6.2	0.549	-0.8	±	4.3^{T}	0.251	-2.7	±	5.3^{T}	Unclear
	PAS	45.2	±	5.8	46.1	±	6.3		2.0	±	4.3^{T}					
Muscle contractile properties																
Dm [mm]	ACT	7.1	±	2.0	7.3	±	1.2	0.813	4.3	±	17.1^{T}	0.128	7.2	±	8.8^{A}	Possibly +ive
	PAS	7.4	±	1.5	7.1	±	0.9		-2.7	±	8.7^{T}					
V90 [mm · s^{-1}]	ACT	145	±	38	140	±	20	0.305	-2.8	±	15.7^{T}	0.548	2.7	±	9.3^{T}	Unclear
	PAS	151	±	33	141	±	23		-5.3	±	11.0^{T}					

ACT, Active recovery; PAS, Passive recovery; CP85, CP90, and CP95, Clean Pull performed at 85, 90 and 95% of maximum load; CMJ, Countermovement Jump; Dm, maximal radial Displacement of the muscle belly; V90, mean Velocity of muscle contraction.
[a]calculated from adjusted pre-values; **A** Indicates small effect size (ES = 0.20 - 0.59); **T** Indicates trivial effect size (0.00 – 0.19).

stress (MS), showing a possibly to very likely more decreased PPC and a possibly to very likely more increased MS after almost each ACT intervention compared with PAS. Interestingly, prior to the afternoon training session (pre T2 and pre T4), jump performance was likely to very likely increased in the PAS condition. This however was only evident pre T4 in ACT, while changes in CMJ height pre T2 were very likely lower in ACT compared to PAS.

Individual Pre-Post changes in markers of sport-specific performance (CP85, CP90, and CP95) of some athletes are shown in **Fig. 6**. Subject #1 showed a likely improved performance in CP85 and CP90 following ACT, while performance in CP90 was likely decreased following PAS. This was accompanied by higher ratings of perceived recovery (PPC and OR) in ACT compared with PAS. In contrast, subject #8 showed a likely decreased performance in CP95 and CP90 after the ACT intervention, while changes in overall performance remained trivial in the PAS intervention. This came also along with increased

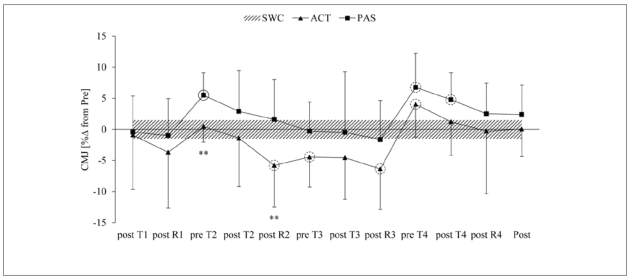

Figure 3. Differences in percentage changes from Pre between ACT and PAS in Countermovement Jump (CMJ) performance during the entire training period. Data are mean ±SD. SWC , Smallest Worthwhile Change (SWC = 0.5 x CV); ACT, Active recovery; PAS, Passive recovery; T, Training session, R, Recovery intervention; circles in dashed and solid lines represent likely and very likely changes from Pre; **indicates very likely between-ACT-PAS difference.

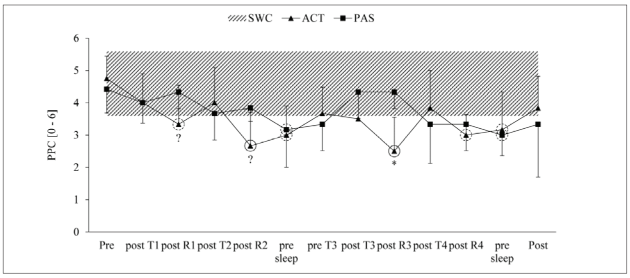

Figure 4. Differences in changes from Pre between ACT and PAS in perceived PPC (Physical Performance Capability) during the entire training period. Data are mean ± SD. SWC, Smallest Worthwhile Change (SWC = 1 point score); ACT, Active recovery; PAS, Passive recovery; T, Training session; R, Recovery intervention; circles in dashed and solid lines represent likely and very likely changes from Pre; ?indicates possibly between-ACT-PAS difference; *indicates likely between-ACT-PAS difference.

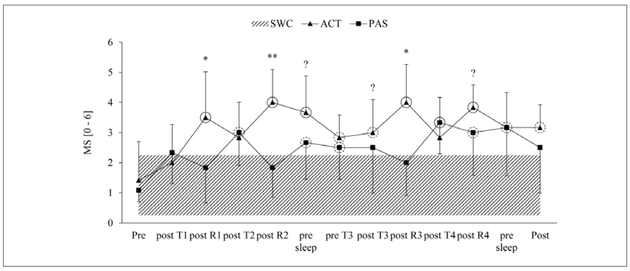

Figure 5. Differences in changes from Pre between ACT and PAS in perceived MS (Muscular Strain) during the entire training period.
Data are mean ± SD. SWC, Smallest Worthwhile Change (SWC = 1 point score); ACT, Active recovery; PAS, Passive recovery; T, Training session; R, Recovery intervention; circles in dashed and solid lines represent likely and very likely changes from Pre; ?indicates possibly between-ACT-PAS difference; *indicates likely between-ACT-PAS difference; **indicates very likely between-ACT-PAS difference.

and decreased ratings of perceived stress (MS and OS) in ACT and PAS, respectively. With regard to subject #3, overall performance was likely to most likely impaired following the PAS condition, whereas performance was only compromised to a lesser extent in CP85 following the ACT condition. In addition, this was supported by a greater increase in ratings of perceived stress in PAS compared to ACT. For the remaining participants, there were no beneficial or deleterious effects of ACT compared with PAS on markers of sport-specific performance.

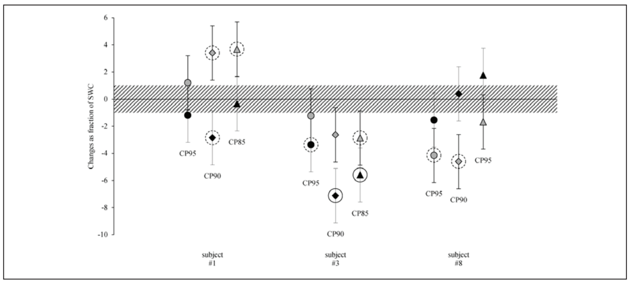

Figure 6. Individual Pre-Post changes in markers of sport-specific performance of participants #1, #3 and #8.
Data are individual change scores ± typical error, expressed as fraction of the SWC; SWC, Smallest Worthwhile Change; CP95, CP90 and CP85, Clean Pull performed at 95%, 90%, and 85% of the maximum load; ACT, Active recovery; PAS, Passive recovery; grey colored symbols represent the ACT and black colored symbols the PAS condition; circles in dashed and solid lines represent likely and very likely Pre-Post changes.

DISCUSSION

This study investigated the short-term effectiveness of the repeated use of ACT on sport-specific performance as well as on neuromuscular, biochemical and perceptual measures in Olympic weightlifters during a 2-day high-intensity training microcycle. Contrary to our initial hypothesis, ACT had no significant beneficial or deleterious group effects compared to PAS on the recovery pattern of performance and selected markers of fatigue. This is similar to a study from our research group, demonstrating no recovery-promoting impact of an ACT strategy in competitive tennis players during a 4-day high-intensity interval training shock microcycle **[29]**. However, overall neuromuscular performance (i.e., CMJ) seemed to be more affected in ACT than in PAS, associated with similar responses in markers of perceived recovery (i.e., PPC) and stress (i.e., MS). Moreover, individual analyses revealed that some athletes may be more likely to benefit from either ACT or PAS. In two of the participants ACT seemed to improve sport-specific performance or could at least promote recovery more effectively after the training period, whereas in another athlete, performance was restored more rapidly following PAS. These findings highlight the importance of analyzing the effectiveness of the present recovery interventions at the individual level. Furthermore, results showed that the 2-day training program induced considerably negative effects on several markers of fatigue (i.e., CK, DOMS, PPC, OR, MS, and OS) irrespective of recovery mode, combined with slight decreases in sport-specific performance (i.e., CP85, CP90, and CP95). Our results are in line with previous research, showing similar impacts on performance as well as on markers of muscle damage and measures of subjective well-being following intense strength training sessions **[4, 30]**.

The study found large to very large increases in CK and DOMS from Pre to Post-training both in the ACT and PAS condition **(Table 2)**. These changes could be attributed to the mechanical disruption of muscle contractile components and the subsequent inflammatory response as a result of intense training load during the preceding days **[31]** suggesting that CK and DOMS were sensitive to detect training-induced fatigue. ACT strategies hastens recovery by increase in local blood flow which promotes nutrient transport to damaged tissues and enhances removal of waste products and muscle-cell debris, as well as by causing a transient analgesic effect on perceived muscle soreness **[7, 9, 10]**. However, our results did not support these recovery mechanisms since the repeated use of ACT was not more effective than PAS in enhancing the clearance rate of CK or alleviating the sensation of DOMS **(Table 2)**. While a previous study also reported no beneficial effects of post-competition ACT on changes in CK concentrations or ratings of muscle soreness in elite female soccer players **[15]** or male futsal and football players **[16, 17]**, Gill et al **[13]** demonstrated that ACT immediately performed after a rugby match significantly decreased the CK activity after 36 hours and 84 hours in elite male players, as compared to PAS. However, in that study the CK activity was analyzed by transdermal exudate sampling, a measurement technique which has not yet been validated **[7]**, making it difficult to compare the present CK values obtained from the blood serum with those reported by Gill et al. **[13]**. Regarding the analgesic effect of ACT on muscle soreness, a study **[10]** showed that muscle soreness was alleviated immediately after light concentric exercise 1 to 4 days after strenuous eccentric exercise of the arm flexors. Similarly, Andersen et al. **[32]** found that ACT provided acute relief of muscle soreness up to 60 minutes following mild elastic tubing 48 hours after maximal eccentric contractions for the upper trapezius. The underlying potential mechanisms of exercise-induced pain relief are believed to be associated with several central neural mechanisms **[33]**. In this context, the activation of the endogenous opioid system during exercise, causing an enhanced endorphin release by neurons in the central nervous system, may inhibit the transmission of pain, and thus increasing the pain threshold and pain tolerance **[10, 33]**. Furthermore, exercise-related increased input from group Ia, Ib and II muscle afferents could interfere with the pain sensations associated with group III and IV afferent activity, probably by interneurons that presynaptically inhibit nociceptive input from ascending pathways at the level of the spinal cord **[10, 33]**. However, the analgesic effect of exercise is thought to be temporary and not long-lasting, since with the cessation of exercise, muscle soreness may gradually return during the post-exercise period **[32, 33]**. This could explain why in the current study the repeated use of ACT immediately performed after each training session was ineffective to reduce the sensation of DOMS in the days after its application. Previous research also reported no sustained effects of ACT on relieving muscle soreness **[15-17]**. Based on the conditions of this study, the present ACT strategy comprising 15 minutes of submaximal whole-body rowing exercise was not more beneficial than PAS. We therefore do not have a conclusive basis to recommend ACT for accelerating muscle tissue recovery or attenuating muscle soreness. However, it should be noted that ACT did not have detrimental effects on the two measures, CK and DOMS.

The 2-day training program also induced meaningful fatigue effects in perceptual markers of the SRSS, demonstrating a decrease in perceived recovery (i.e., PPC and OR) and an increase in perceived stress (i.e., MS and OS) in both recovery interventions. However, there were no differences in Pre-Post changes between ACT and PAS **(Table 2)** suggesting that the subjective markers were sensitive to reflect changes in training-related fatigue, irrespective of recovery mode, and ACT may not be a more effective strategy to decrease the magnitude of fatigue or speed-up recovery at the perceptual level, as compared to PAS. Our observations are in line with those in the study of Tessitore and associates **[16]**, reporting no beneficial effects of post-game ACT on the recovery-stress state of male futsal players. Conversely, a study by Suzuki et al. **[14]** showed that low-intensity ACT immediately after a rugby match favored a better psychological recovery. This contradictory finding may be related to the different rating scale used to assess the athlete's psychological condition, making comparisons difficult. In this regard, Suzuki and colleagues **[14]** used the Profile of Mood States and showed a decreased tension score in the ACT group 48 hours post-competition. However, this was the only significant effect on participants' mood states among six different subscales, and that observed within-group change was not significantly different from the control group. This raises concerns on the effectiveness of ACT on accelerating mental recovery. The present results indicate, however, that the repeated use of ACT during a short period of intense training does not adversely or favorably affect markers of perceived recovery and stress, allowing its application after careful consideration by coaches and practitioners.

Regarding measures of performance, the current study demonstrated that maximal barbell velocity in CP over all relative intensities (CP85, CP90, and CP95) slightly decreased from Pre to Post-training both in ACT and PAS **(Table 2)**. It is assumed that the overall decline in CP performance could be related to the specific fatiguing load of the preceding high-intensity training sessions. This may hamper the production of very high peak forces and contractile rates of force development, probably resulting in less peak power outputs during the execution of the CPs. Conversely, CMJ did not reflect changes in training-induced fatigue, since jump performance remained unaffected after the training period in both recovery conditions **(Table 3)**. In this regard, it has been speculated that athletes might be capable to generate 'one-off' effort close to their maximum during a single jump test, although being in a fatigued condition **[16]**. Additionally, Häkkinen et al **[4]** found no systematic changes in the basic level of neuromuscular performance (i.e., maximal isometric force and maximal electromyographic activity of leg extensor muscles) during an intensive 1-week strength training period in elite weightlifters. Our results showed that ACT had no beneficial or deleterious effects on all measures of performance, evidenced by no differences in Pre-Post changes between ACT and PAS **(Table 3)**. Furthermore, ACT did not enhance the proposed recovery mechanisms, and thus did not promote post-training recovery suggesting limitations in the use of ACT in strength and power athletes. It is however possible that a 2-day training period may be too short to induce sufficient fatigue in the performance measures, which might adversely affect the possibly short-term recovery-promoting effect of an ACT strategy **[16]**. Furthermore, our findings are in agreement with previous studies which demonstrated that post-match ACT did not positively or adversely affect the recovery pattern of neuromuscular performance in female and male team sport players **[15-17]**. Consequently, we recommend that coaches and practitioners should exercise caution and a sense of subjective judgment in the use of ACT for promoting recovery.

The muscle contractile properties (Dm and V90) determined using TMG remained unaffected after the training program in both recovery interventions **(Table 3)** indicating that the present TMG measures were insufficient to detect training-induced fatigue. The unimpaired muscle contractile function was unexpected, since changes in CK concentrations and DOMS indicated the presence of muscle damage and soreness. Previous studies have shown that muscle contractility was substantially compromised after high-intensity strength exercise of the elbow flexors as a result of myofibrillar disruptions, followed by the local inflammatory response and impairments in excitation-contraction coupling **[21, 34]**. This however was not evident in the present study, and the findings may in part be explained by the current high inter-individual variability in participants' change scores and the lower severity of exercise-induced muscle damage as well as the differences in methodological design. Our findings are consistent with the findings of Rey et al. **[35]** who showed that immediate post-training ACT did not positively or negatively affect muscle contractile properties 24 hours after training in male soccer players.

Interestingly, the neuromuscular performance (i.e., CMJ) in our participants tended to be more impaired in the ACT than in the PAS condition **(Figure 3)** during the entire training period, reflected by a negative trend in the total mean change of CMJ height in ACT (-1.9 ± 5.1 %) compared to PAS (1.8 ± 4.2 %). Since jump tests represent a valid means to monitor neuromuscular function in athletes, the current findings indicate a greater readiness to perform with PAS **[36]**. Moreover, jump performance seemed to be more adversely affected immediately after ACT in most cases, as compared to PAS. This was also accompanied by similar responses in markers of perceived PPC and MS **(Figs 4-5)**. It is likely that the muscular activity in individualized submaximal rowing ergometer exercise may have led to an acute impairment in CMJ performance. This notion is corroborated by the jump performance increasing meaningfully immediately before each afternoon training session, particularly following the PAS intervention **(Table 3)**. Neuromuscular performance shows diurnal variations with improved performance typically observed in the afternoon and evening compared with the morning **[37]**. This could be causally linked to similar circadian rhythm of the core temperature, peaking in the late after noon, and thereby inducing a passive warm-up effect that may improve muscle contractility. In addition both central (e.g., neural input to the muscles) and peripheral (e.g., contractile state of the muscles) mechanisms that could be altered across the day may also play an important role [37]. It has also been shown that strength training performed in the morning seemed to attenuate the circadian decline in free testosterone, and thus, potentiated neuromuscular performance (i.e., maximal strength, jumping power and sprint times) later in the day, suggesting a hormone-mediated effect on subsequent performance [38].

Regarding individual responses to the recovery interventions **(Figure 6)**, two athletes showed positive responses to ACT. Subject #1 showed improvements in markers of sport-specific performance after the training period associated with higher ratings of perceived PPC and OR in ACT compared with PAS. For subject #3, ACT seemed to faster accelerate post-training recovery from training-induced fatigue, evidenced by a less pronounced drop in markers of sport-specific performance and a lower increase in perceived MS and OS after the training program, as compared to PAS. However, subject #8 appeared not to benefit from ACT with decreases in markers of sport-specific performance and increased rating of perceived MS and OS after the training program in ACT, as compared to PAS. Therefore it may be practically purposeful to adopt an individual-based approach to determine the effectiveness of ACT in the longer-term.

There are limitations to the present study that need to be considered. The two microcycles could not be precisely standardized, and therefore equated by volume, intensity and exercise selection, since athletes' individual training protocols were exclusively designed by the national head coach, which were beyond our control. However, total training load and mean barbell load showed only trivial differences between the two microcycles as well as between the ACT and PAS modality **(Figure 2)**. It may therefore be assumed that slight variations in training program design did not affect the outcome of this study. Furthermore, we are aware of the low sample size of the current study. However, this study was performed with a competitive high-quality sample, and given that there are not as many elite German Olympic weightlifters, increasing sample size was therefore almost impossible. Therefore we decided to report individual responses to the two recovery interventions analyzed in order to improve the decision-making process in terms of the effectiveness of ACT.

CONCLUSION

The repeated use of post-training ACT consisting of submaximal rowing ergometer exercise for 15 minutes had no beneficial or deleterious effects on the recovery pattern of sport-specific performance as well as on neuromuscular, physiological and perceptual markers of fatigue in elite German Olympic weightlifters during a 2-day high-intensity microcycle, as compared to PAS. In a short-term perspective, this may allow the application of ACT according to athletes' and coaches' individual preferences, experiences or beliefs. Additionally, if ACT is not being considered, practitioners should also be open to other recovery modalities to limit the severity of training-induced fatigue. However, this study provided evidence of variable individual responses to the recovery interventions, showing both beneficial and detrimental effects of ACT on performance. Therefore, the short-term implementation of an ACT program should be thoroughly considered at the individual level. In this regard, it may be also useful to closely monitor the athlete's perceived recovery and stress status, since both measures appear to be sensitive for reflecting changes in sport-specific performance. Future research, particularly in strength and power dominated sports, is required to evaluate the longer-term effects of ACT on physical and perceptual fatigue recovery, taking into account each athlete's individual response.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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