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Anaerobic speed reserve and acute responses to a short-format high-intensity interval session in runners

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ABSTRACT

Objectives: This study aimed to assess relationships of acute responses to short-format high-intensity interval training (HIIT) with the anaerobic speed reserve (ASR) of adolescent runners.
Design: Pre-post intervention design.
Methods: Eighteen highly-trained youth runners (15.83 ± 0.86 years) underwent maximal sprinting speed (MSS) and maximal aerobic speed (MAS) assessments to determine ASR (MSS minus MAS) and a standardized HIIT protocol ($2 \times (20 \times 15$ s/15 s @110 % MAS)) was administered. Pre/post-HIIT assessments included biochemical (i.e., creatine kinase (CK)), neuromuscular (countermovement jump, CMJ; reactive strength index, RSI), cardiac (i.e., heart rate recovery (HRR)), and athlete-reported outcome measures (e.g., single item for fatigue). Pearson's r was calculated to assess relationships between acute responses and ASR, MSS, MAS, and relative intensity of the HIIT (%ASR).
Results: Athletes' ASR and %ASR were significantly associated with the pre/post difference of CK ($r = -0.75$; $p < 0.001$; $r = 0.74$; $p < 0.001$, respectively), CMJ height, and RSI ($r \geq 0.69$; $p \leq 0.002$; $r \leq -0.49$; $p \leq 0.04$, respectively). However, HRR did not correlate significantly with ASR or %ASR ($r \leq 0.37$, $p \geq 0.131$, $r \geq -0.31$; $p \geq 0.22$, respectively). The pre/post difference of RSI correlated with MAS ($r = -0.54$; $p = 0.02$), and the pre/post difference of CK ($r = -0.50$; $p = 0.034$) and of CMJ height ($r = 0.76$; $p < 0.001$) with MSS. Regarding athlete-reported measures, ASR and %ASR showed significant associations with most fatigue and recovery variables ($r \geq 0.57$; $p \leq 0.014$, $r \geq 0.57$; $p \leq 0.013$, respectively). The pre/post difference of the single item for fatigue showed a positive relationship with MSS ($r = 0.49$; $p = 0.037$).
Conclusions: Acute biochemical, neuromuscular, and athlete-reported responses to short-format HIIT showed strong relationships with ASR and MSS, indicating higher internal load in athletes with a lower ASR and MSS by using a higher %ASR, compared to athletes with a higher ASR and MSS. These findings can help to tailor training programs to individual needs and avoid possible overload.

Practical implications

- Coaches and practitioners should be aware that runners with a lower ASR (and MSS) show a higher acute internal (objective and athlete-reported) response to a high-intensity exercise, even when this exercise is normalized on their MAS but demanding a higher %ASR during the exercise compared to athletes with a higher ASR (and MSS). This can be of high relevance for athletes and coaches for explaining differences in acute responses and to adjust the training cycle and stimuli to best meet an athlete's requirements.
- We recommend that a different form of short-format HIIT prescription (e.g. based on %ASR) might be more suitable for the athletes with a

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Abbreviations: ASR, anaerobic speed reserve; CK, creatine kinase; CMJ, countermovement jump; CPET, cardiopulmonary exercise testing; DJ, drop jump; HIIT, high-intensity interval training; HRR, heart rate recovery; MAS, maximal aerobic speed; MSS, maximal sprinting speed; r, Pearson's correlation coefficient; RPE, ratings of perceived exertion; RSI, reactive strength index; SRR, speed reserve ratio; $t90\%HR_{max}$, time spent above 90 % of HR_{max}; $t90\%\dot{V}O_{2max}$, time spent above 90 % of $\dot{V}O_{2max}$; $\dot{V}O_{2max}$, maximal oxygen uptake; %ASR, relative intensity of HIIT, i.e., percentage of ASR.

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lower ASR and would overall lead to more homogenous responses in a group of athletes with different ASR types.
- Higher volumes and lower intensities might be best for endurance-oriented runners or lower volumes and higher intensities speed-oriented runners.

1. Introduction

High-intensity running is a common requirement in competitive sports, demanding an integration of various metabolic systems as well as neuro-mechanical capabilities. The ability to perform and cope with high-intensity interval training (HIIT) is thus crucial in most running-based sports such as sprinting, middle-distance running, or team sports.[1]

However, the tolerance toward HIIT is dependent on different factors such as muscle fiber type distribution[2] or cardiorespiratory and metabolic capacities as determined by for example the maximal oxygen uptake ($\dot{V}O_{2max}$) or the first velocity at $\dot{V}O_{2max}$, i.e., the maximal aerobic speed (MAS).[1] While the $\dot{V}O_{2max}$ and MAS are limited to describing aerobic, oxidative capacities and performances, the anaerobic speed reserve (ASR) reflects the difference between MAS and the maximal sprinting speed (MSS) which incorporates neuro-mechanical, coordinative and glycolytic capabilities. Thus, it was previously suggested that athletes can be categorized in different locomotor profiles, i.e., athletes with a high ASR, high MSS, and low MAS are referred to as sprint types, athletes with a low ASR, low MSS, and high MAS as endurance types, and athletes with a moderate ASR, moderate MSS, and moderate MAS as hybrid types.[3,4] Additionally, the ASR is increasingly used for prescribing HIIT and has shown to result in more homogeneous chronical adaptations across team sport athletes[5,6] and acute adaptations across team sport athletes and runners compared to MAS-prescribed HIIT.[7,8] Furthermore, it is assumed that the ASR together with its components (i.e., MAS and MSS) is a good predictor for the individual tolerance to HIIT.[9]

These assumptions are based on a previous study showing that running time to exhaustion during different high-intensity runs based on MAS is better explained by the percentage of ASR used during that run than the percentage of MAS indicating that the ASR may be a better predictor for tolerance to high-intensity exercise than the MAS.[10] In contrast, Buchheit et al.[9] found that a higher amount of completed sets of a HIIT until exhaustion by different recreational team sport players is associated with a higher $\dot{V}O_{2max}$ and MAS, while the ASR only has an influence if adjusted for differences in MAS. These results highlight the importance of considering the underpinning qualities of MAS and MSS in addition to the ASR when explaining differences in acute responses or performance differences. Besides considering performance outcomes such as time to exhaustion, acute responses such as cardiorespiratory (e.g., time spent at or near $\dot{V}O_{2max}$, maximal heart rate), biochemical (e.g., creatine kinase (CK), blood lactate concentration), neuromuscular (e.g., jumping performance), and acute athlete-reported outcomes (e.g., rating of perceived exertion (RPE)) can be helpful in evaluating the individual tolerance to HIIT.[1,3,9,11] Additionally, the heart rate recovery (HRR) after an exercise was previously used as an indirect and further measure of acute load, because it is associated with blood lactate accumulation and muscle acidosis.[12]

In the context of ASR, a lower MAS and a higher percentage of ASR used during repeated sprinting led to a higher blood lactate concentration after and percentage used of $\dot{V}O_{2max}$ during HIIT, while the athletes' MSS did not affect these acute responses.[9] Additionally, the heart rate recovery (HRR) after repeated sprinting seems to be associated with the ASR in athletes of different disciplines, however, these results are inconclusive due to sex differences.[13] Interestingly and in contrast, athletes from a sprint or endurance background did not show differences in acute responses to short and long format HIIT based on MAS related to the cardiac autonomic regulation, inflammation, or muscle damage.[1] Regarding athlete-reported outcome measures after short- or long-format HIIT or after repeated sprinting, RPE seems to not be influenced by the locomotor profile (i.e., ASR, MAS, and MSS)[9] or the type of runner (i.e., endurance versus sprint athletes, based on the targeted competition).[1]

While individualization of HIIT based on profiling could enhance training processes by applying the optimal degree of external load,[5] knowledge about the individual tolerance to HIIT could provide additional information for the optimal prescription of HIIT, e.g. to avoid overload. Since several studies previously reported more homogeneous adaptations based on ASR-prescribed HIIT compared to MAS-based HIIT, we assume that individual locomotor profiles (i.e., characterized based on ASR, MAS, and MSS) are related to acute responses to MAS-based HIIT. However, in practice, MAS-based prescription of HIIT is still very commonly used, as it represents one way to normalize the intensity of HIIT. Therefore, we aimed to assess associations of acute cardiorespiratory, neuromuscular, biochemical, and athlete-reported fatigue, stress, and recovery responses to short-format HIIT normalized according to MAS with the ASR and its components (i.e., MAS and MSS) in adolescent runners.

2. Methods

2.1. Participants

In this study, N = 18 adolescent female and male (female n = 7; weight 59.21 ± 8.21 kg; height 1.75 ± 0.08 m; age 15.83 ± 0.86 years; training 8.64 ± 2.65 h per week; expertise 7.22 ± 2.92 years of systematic training; $\dot{V}O_{2max}$ 55.17 ± 4.08 mL/min/kg) 400-m and middle-distance runners classified as tier three athletes (highly trained)[14] and familiar with HIIT were included. This study was approved by the local ethics committee (Approval Number: 22-10). The participants and their legal guardians were informed about the procedures and possible risks and agreed to participate by signing a consent form.

2.2. Design

The participants completed the different measures at two different visits. At their first visit, each athlete underwent a standardized warmup before they conducted two 60-m sprints with 20-min rest to assess the MSS (=the fastest sprinting speed out of the two sprints). Following a 30-min passive rest, the participants performed a cardiopulmonary exercise test (CPET) on a treadmill to assess the MAS and $\dot{V}O_{2max}$. On a second visit after two to five weeks, the participants conducted a short-format HIIT while several measurements pre (biochemical, neuromuscular, cardiac, and athlete-reported fatigue, stress, and recovery measures), during (cardiopulmonary measures), post (biochemical, neuromuscular, cardiac, and athlete-reported fatigue, stress, and recovery measures), and 24-h delayed (athlete-reported fatigue, stress, and recovery measures) were performed to determine the individual responses to the HIIT.

2.3. Methodology

2.3.1. Sprint testing

The 60-m sprints were implemented either on an outdoor or indoor Tartan™ track depending on the available location of the athletes. The athletes started sprinting in a standing position with a self-timed start and the velocity was continually recorded with a radar gun (Stalker ATS II; 46.875 Hz; Richardson; USA).[15] The radar gun was placed on a waist-high tripod 2 m behind the start. The data were first processed with the manufacturer's software. Using a custom-made R Studio[16] script, speed-time curves were then fitted by a biexponential function to calculate MSS.[17]

2.3.2. Cardiopulmonary exercise testing

The CPET on a treadmill (PPSmed 55, PPSmed L70, 4front, or ST 4front; WOODWAY GmbH; Weil am Rhein; Germany) started at 8 km/h with a constant incline of 1 % and increased every minute by 1 km/h until subjective exhaustion of the participants.[18] Breath-by-breath ventilatory data were obtained using the Metalyzer 3B or MetaMax 3 spirometer (Cortex Biophysik GmbH; Leipzig; Germany). A 15-second moving average filter was used for further analysis.[19] Gas sensors were calibrated using gases of known concentrations (15 % O_2, 5 % CO_2), and the turbine volume transducer was calibrated using a 3-l syringe (Cortex Biophysik GmbH; Leipzig; Germany). The $\dot{V}O_2$-data were first examined for a plateau which is defined as a lower increase in $\dot{V}O_2$ than 150 mL/min in the last minute of exercise[20]; $\dot{V}O_{2max}$ was assessed as the highest 30-s-interval of $\dot{V}O_2$.[21] Physical exhaustion and thus $\dot{V}O_{2max}$ were checked using several parameters: The highest respiratory exchange ratio (RER_{end}; quotient of $\dot{V}CO_2/\dot{V}O_2$) at the end of the exercise, maximal heart rate (HR_{max}) using a chest strap (H7 or H10; Polar Electro; Kempele; Finland), and session ratings of perceived exertion (sRPE; scale 6–20) after test termination. Immediately at the end, 3 min, and 5 min after the test, 20 μL of capillary blood was collected from the right earlobe to assess the maximal lactate concentration after the treadmill test (La_{max}) and analyzed using the BIOSEN C-Line (EKF Diagnostic; Barleben; Germany). Confirmation of physical exhaustion required meeting at least two of the following criteria: $RER_{end} \geq 1.0$; $sRPE \geq 17$; $HR_{max} \geq 210$-age, $La_{max} \geq 8$ mmol/L, and reaching a $\dot{V}O_2$-plateau. The MAS represents the first (interpolated) velocity when reaching this plateau.[15,20]

ASR was determined as the speed difference between MSS and MAS. For further describing the sample, the speed reserve ratio (SRR) was quantified as the quotient of MSS and MAS.

2.3.3. High-intensity interval session

On a treadmill, the participants performed a warmup of 2 min at 70 % MAS and 3 min at 90 % MAS. Immediately after the warmup, the participants underwent a HIIT consisting of two sets with 20 repetitions of running 15 s at 110 % of the individual MAS and 15 s of passive rest.[22] In between sets, the participants rested for 2 min. The participants' breath-by-breath ventilatory data were again obtained using the Metalyzer 3B or MetaMax 3 spirometer and a 15-s moving average filter. The HR was recorded using a chest strap. To check the participants' cardiorespiratory load during the HIIT, the times spent >90 % of HR_{max} (t90% HR_{max}) and >90 % of $\dot{V}O_{2max}$ (t90%$\dot{V}O_{2max}$) were assessed.[3,23]

2.3.4. Biochemical, neuromuscular, cardiac, and athlete-reported measures

Thirty minutes prior to and after the HIIT, 20 μL of capillary blood was collected from the fingertip and analyzed with the SimplexTAS™ 101 Analyser (TASCOM; Gyeonggi-do, Korea) to assess plasma creatine kinase (CK) activity. In addition, the participants performed three countermovement jumps (CMJ) to assess maximal CMJ height and three drop jumps (DJ; 30 cm height) to assess the maximal reactive strength index (RSI = jump height/contact time) on a Hawkin Dynamics, Inc. force plate (Westbrook, Maine, USA)[24] 10 min before and after the HIIT. To monitor the cardiac response, the HRR was documented from the end to 1 min post (HRR1′) and from 1 min post to 2 min post HIIT (HRR2′). Additionally, the participants completed the Short Recovery and Stress Scale (SRSS) consisting of four dimensions each regarding recovery (physical performance capability, mental performance capability, emotional balance, and overall recovery) and stress (muscular stress, lack of activation, negative emotional state, and overall stress) pre and post HIIT. The rating scale ranged from 0 (does not apply at all) to 6 (fully applies).[25] The participants answered a single item for fatigue rated on a bipolar response option (−3 = much worse than normal; 0 = normal; +3 = much better than normal)[26] and the sRPE before and immediately after the HIIT. The SRSS and the single item for fatigue were additionally assessed 24 h after the HIIT.

2.4. Statistical analysis

Statistical analysis was carried out with RStudio (R version 4.3.2, R Foundation for Statistical Computing, Vienna, Austria).[16] The Pearson's correlation coefficient was calculated to detect relationships between the pre/post changes in the acute response variables and the predictor variables ASR, MAS, MSS, the relative portion of ASR during the HIIT (%ASR), and $\dot{V}O_{2max}$, and between ASR and the anthropometrics, MAS, MSS, $\dot{V}O_{2max}$, and the cardiopulmonary responses during the HIIT using the 'cor.test' function in the 'stats' package.[16] According to Hopkins,[27] the magnitude of the correlation was considered to be small ($0.1 \leq r < 0.3$), medium ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and almost perfect ($r \geq 0.9$) classifications. For an additional analysis of differences in acute responses between athletes with a high and low ASR (using k-means clustering), a two-way analysis of variance was conducted (see statistical analysis and results in Supplementary Material, Supplementary Tables 1, 2, and 3 and Supplementary Fig. 1). For all calculations, the significance level was set at $\alpha = 0.05$ and 95 % confidence intervals (CI) were included.

3. Results

3.1. Descriptive results

The descriptive results related to the anthropometrics, CPET and sprinting outcomes, and the cardiovascular responses during the HIIT are presented in Table 1. MSS ($r = 0.79$), SRR ($r = 0.89$), and %ASR for the intensity during the HIIT ($r = -0.92$) showed very large to almost perfect relationships with the ASR.

3.2. Results for biochemical, neuromuscular, and cardiac response

The cardiorespiratory responses during the HIIT, i.e., t90%HR_{max} and t90%$\dot{V}O_{2max}$, did not show any relationships with ASR (see Table 1). The relationships between the pre/post differences of the acute responses and ASR, MAS, MSS, and %ASR are presented in Figs. 1, 2, 3, and 4 respectively, and a descriptive visualization of the association of the pre/post differences with MAS and MSS is shown in Fig. 2. The pre/post difference of CK showed a very large relationship with ASR ($r = -0.75$ see Fig. 1). In addition, large to very large correlations were found between the pre/post difference in CMJ height ($r = 0.69$) and in RSI ($r = 0.79$) and the ASR. However, the HRR and the ASR did not correlate ($r \leq 0.37$). Regarding the relative intensity of the HIIT, medium to very large associations were found between the pre/post differences of CK ($r = 0.74$), CMJ height ($r = -0.49$), and RSI ($r = -0.84$) and the % ASR. The pre/post differences of any of the objective variables did not correlate with $\dot{V}O_{2max}$ ($r \leq 0.33$; see Supplementary Fig. 2), whereas the pre/post difference of RSI showed a negative relationship with MAS ($r = -0.54$, see Figs. 2 and 4) and MSS ($r = -0.50$; see Figs. 3 and 4). The pre/post difference of CMJ height showed a positive correlation with MSS ($r = 0.76$).

3.3. Results for athlete-reported measures

The pre/post differences of the single item for fatigue, Physical Performance Capacity, Muscular Stress, and Overall Stress showed medium to very large correlations with ASR ($r \geq |0.49|$; see Fig. 1). However, the pre/post difference of the sRPE did not show a significant relationship with ASR ($r = -0.16$; see Fig. 1). Similarly, the pre/post differences of the single item for fatigue, Physical Performance Capacity, and Muscular Stress were significantly correlated with %ASR ($r \geq |0.57|$; see Fig. 4). The pre/post differences of any of the athlete-reported variables did not correlate with $\dot{V}O_{2max}$ and MAS ($r \leq 0.45$; see Figs. 2 and 3, and Supplementary Fig. 2), while the pre/post difference of the single item for fatigue showed a positive relationship with MSS ($r = 0.49$; see Figs. 3 and 4).

Table 1

Descriptive results of anthropometrics, CPET and sprinting outcomes, and cardiovascular response during the HIIT and relationships of these variables with the ASR.

	Age [years]	Mass [kg]	Height [m]	WA scores	$\dot{V}O_{2max}$ [mL/min/kg]	MAS [km/h]	MSS [km/h]	ASR [km/h]	SRR	110%MAS [km/h]	%ASR	t90%$\dot{V}O_{2max}$ [s]	t90%HR_{max} [s]
	Mean ± SD (min–max)												
N = 18	15.89 ± 0.76 (15.00–17.00)	59.00 ± 8.00 (45.00–70.00)	1.75 ± 0.08 (1.62–1.89)	799 ± 92 (598–887)	55.20 ± 4.10 (47.00–63.00)	16.17 ± 1.58 (12.50–19.25)	31.67 ± 2.44* (27.14–35.85)	15.50 ± 2.48 (10.89–19.60)	1.91 ± 0.21* (1.62–2.38)	17.78 ± 1.73 (13.75–21.18)	10.74 ± 2.22* (6.92–14.92)	43 ± 46 (0–195)	1046 ± 136 (800–1200)

CPET – cardiopulmonary exercise testing; MAS – maximal aerobic speed; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; SRR – speed reserve ratio; $\dot{V}O_{2max}$ – relative maximal oxygen update; %ASR – 110%MAS, i.e., intensity of high-intensity interval training (HIIT), relative to ASR; t90%$\dot{V}O_{2max}$ – time spent above 90 % of $\dot{V}O_{2max}$ during HIIT; t90%HR_{max} – time spent above 90 % of HR_{max} during HIIT; SD – standard deviation; min – minimum; max – maximum; WA-scores – scores based on the World Athletic scoring system.

* Indicates $p < 0.001$, i.e., significant correlation with ASR.

4. Discussion

4.1. Main findings

This study aimed to assess relationships between acute responses of physiological and athlete-reported outcome measures to short-format, MAS-based HIIT and the ASR in adolescent runners. The main findings of the present study were: (1) ASR was negatively associated with the %ASR during the HIIT, while t90%HR_{max} and t90%$\dot{V}O_{2max}$ did not show any relationship with ASR; (2) ASR and %ASR showed a negative relationship with the pre/post difference of CK and a positive relationship with the pre/post difference of CMJ height and RSI; (3) the single item for perceived fatigue, Physical Performance Capacity, and Overall Recovery were positively and the Muscular Stress negatively associated with ASR and %ASR; (4) the pre/post changes did not correlate with $\dot{V}O_{2max}$, while only the changes in RSI correlated with MAS, and the changes in CK, CMJ height, and the single item for fatigue with MSS.

4.2. Acute biochemical, neuromuscular, and cardiac response

The MAS-based HIIT protocol used in the present study led to similar cardiorespiratory responses, i.e., t90%HR_{max} and t90%$\dot{V}O_{2max}$, during the HIIT in runners with different ASR (see also Supplementary Table 1). Although the relative intensity of the HIIT as reflected by %ASR was higher for the athletes with a lower ASR, these results indicate that the cardiorespiratory load during the HIIT was comparable between the different athletes. An explanation for that could be the HIIT design being a short-format of 15 s of load following 15 s of passive rest which potentially has been too short for maximal cardiorespiratory adaptations within the 15 s of work to see potential differences between the athletes.[1] Similar results were previously found for the comparison of endurance and sprint athletes related to the percentage of HR_{max}[1,13] as well as to the percentage of $\dot{V}O_{2max}$ achieved during HIIT.[1] However, previous studies showed low intertrial reliability of t90%HR_{max} and t90%$\dot{V}O_{2max}$,[28,29] indicating that these findings should be interpreted with caution.

Despite similar cardiorespiratory responses during a HIIT, acute biochemical and neuromuscular responses after the HIIT were likely influenced by the athletes' ASR. Athletes with a lower ASR and MSS, showed an increased CK response compared to athletes with a higher ASR and MSS. Since increased levels in CK can be a sign of exercise-induced muscle damage,[1] our results indicate that runners with a lower ASR (and MSS) experienced remarkable muscle damage due to the short-format HIIT, while the higher ASR runners did not. According to Baird et al.,[30] the highest CK level increase occurs in the exercise with the highest intensity and shortest duration, as opposed to a longer-duration, lower-intensity session. This could be explained by the athletes with the lower ASR running the MAS-based HIIT at a higher relative intensity (%ASR) showing higher increases in CK than those with a lower ASR running the HIIT at a lower %ASR. Supported are these findings by the pre/post difference in CK being significantly correlated with %ASR. These results are supported by a higher decrease in CMJ height and RSI in the athletes with a lower ASR and MSS, pointing toward a higher acute neuromuscular load due to the HIIT compared to the runners with a higher ASR and MSS. Interestingly, these differences are mainly influenced by the athletes' ASR and MSS rather than by their $\dot{V}O_{2max}$ or MAS (see Supplementary Fig. 2 and Figs. 2 and 3). Fig. 5 illustrates that athletes with a lower MSS, and therefore a likely lower ASR, showed higher increases in CK and higher decreases in CMJ height and RSI from pre to post HIIT, whereas the MAS does not seem to have much influence. The differences due to an athlete's MSS and ASR in CK, CMJ height, and RSI may be due to differences in buffering or types of muscle fibers.[31] The athletes with a higher MSS and ASR more likely have a higher amount of fast twitch fibers than those with a lower MSS and ASR, which may increase the tolerance to metabolic acidosis.[31] Additionally, an impaired neuromuscular performance is strongly correlated with a decrement in muscle activation,[32] which is in line with lower ASR athletes running at

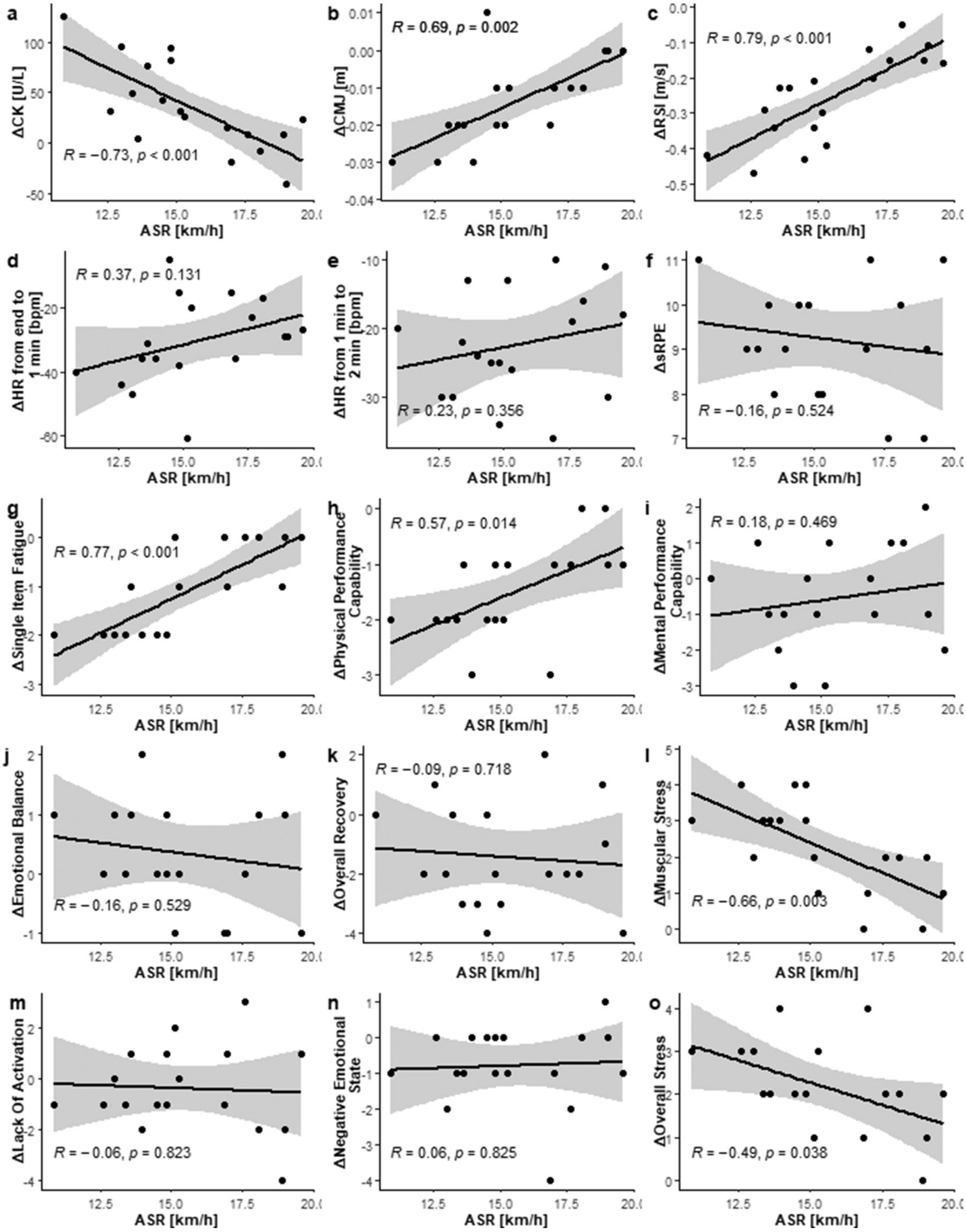

Fig. 1. Scatterplots with regression lines and 95 % confidence intervals (gray area) for ASR with the different objective and athlete-reported variables. ASR – anaerobic speed reserve; Δ – delta, i.e., pre/post difference; CK – creatine kinase; CMJ – countermovement-jump; RSI – reactive strength index; HR – heart rate; sRPE – session ratings of perceived exertion; r – Pearson's r; p – significance value.

a higher relative intensity, %ASR, and showing higher markers for muscle damage, i.e. CK, potentially leading to less muscle activation, whereby the jumping performance is impaired after the HIIT. In contrast, Buchheit et al.[9] found that neither $\dot{V}O_{2max}$ and MAS nor MSS influences the changes of CMJ and DJ height from pre to post HIIT in recreational team sport players. The discrepancies to our findings may be due to the repeated sprinting design of the HIIT inducing a different form of stress compared to the short-format HIIT in our study. Similarly to the athletes' ASR, the large correlations of the pre/post differences of CMJ height and RSI with %ASR indicate that athletes running at a higher percentage of their ASR, due to their higher MAS but lower MSS, experience a higher acute load than those running at a lower proportion of their ASR. Although, MAS-based HIIT represents one way to normalize HIIT, these results were expected as previous studies found more homogenous adaptations when the HIIT was prescribed according to ASR in comparison to MAS.[5–8] Surprisingly, the HRR did not correlate with the ASR and %ASR which was not expected while the HRR is associated with blood acidosis and therefore an indirect measure of acute load.[12] Additionally, these results are contrary to the results of Del Rosso et al.[13] showing slower HRR kinetics in males and faster HRR kinetics in females with a high ASR compared to those with a low ASR. Also, in that study, the participants were rather heterogeneous. The load of the all-out repeated sprint exercise is not directly comparable to the short-format HIIT implemented in our study which can represent different forms of stress. In summary, our results indicate that an athlete's ASR does not affect acute cardiorespiratory responses during high-

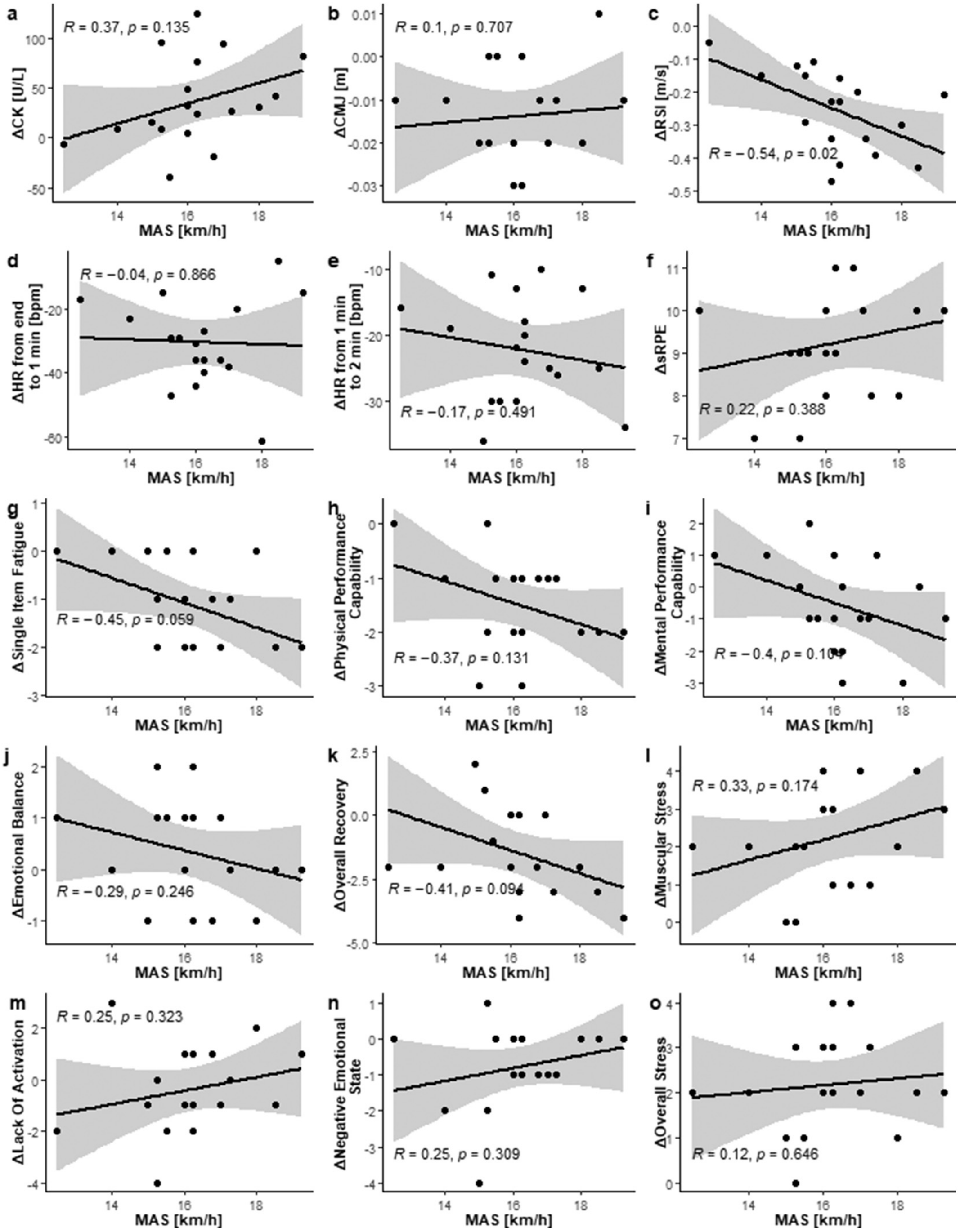

Fig. 2. Scatterplots with regression lines and 95 % confidence intervals (gray area) for MAS with the different objective and athlete-reported variables. MAS – maximal aerobic speed; Δ – delta, i.e., pre-post difference; CK – creatine kinase; CMJ – countermovement-jump; RSI – reactive strength index; HR – heart rate; sRPE – session ratings of perceived exertion; r – Pearson's r; p – significance value.

intensity exercise above MAS, while acute biochemical and neuromuscular responses and therefore the objective tolerance to HIIT differs related to an athlete's ASR and MSS due to using a lower %ASR during the exercise despite a normalized intensity based on MAS or differences in muscle fiber typology.

4.3. Acute athlete-reported response

Here, the pre/post changes in sRPE did not correlate with the ASR suggesting that the perceived load during the HIIT was similar for athletes with a higher and lower ASR. Similar results were found in previous studies showing that sRPE was comparable between sprint and endurance athletes as well as between athletes with a high and low ASR after short-format HIIT,[1,9] while higher sRPE were found after long-format HIIT in endurance compared to sprint athletes.[1] These differences between short- and long-format HIIT resulting in homogeneous and heterogeneous sRPE, respectively, might be explained by the last rest in a short-format HIIT being closer to the end of the HIIT compared to the long-format HIIT. This is also known as the peak-end rule, i.e. athletes tend to judge an experience largely based on how they felt at its most intense point (the “peak”) and at its end, which might be influenced by the last break of a short-format HIIT being close to the end.[33] The single item for fatigue, Physical Performance Capability, and Overall Recovery showed higher decreases and the Overall

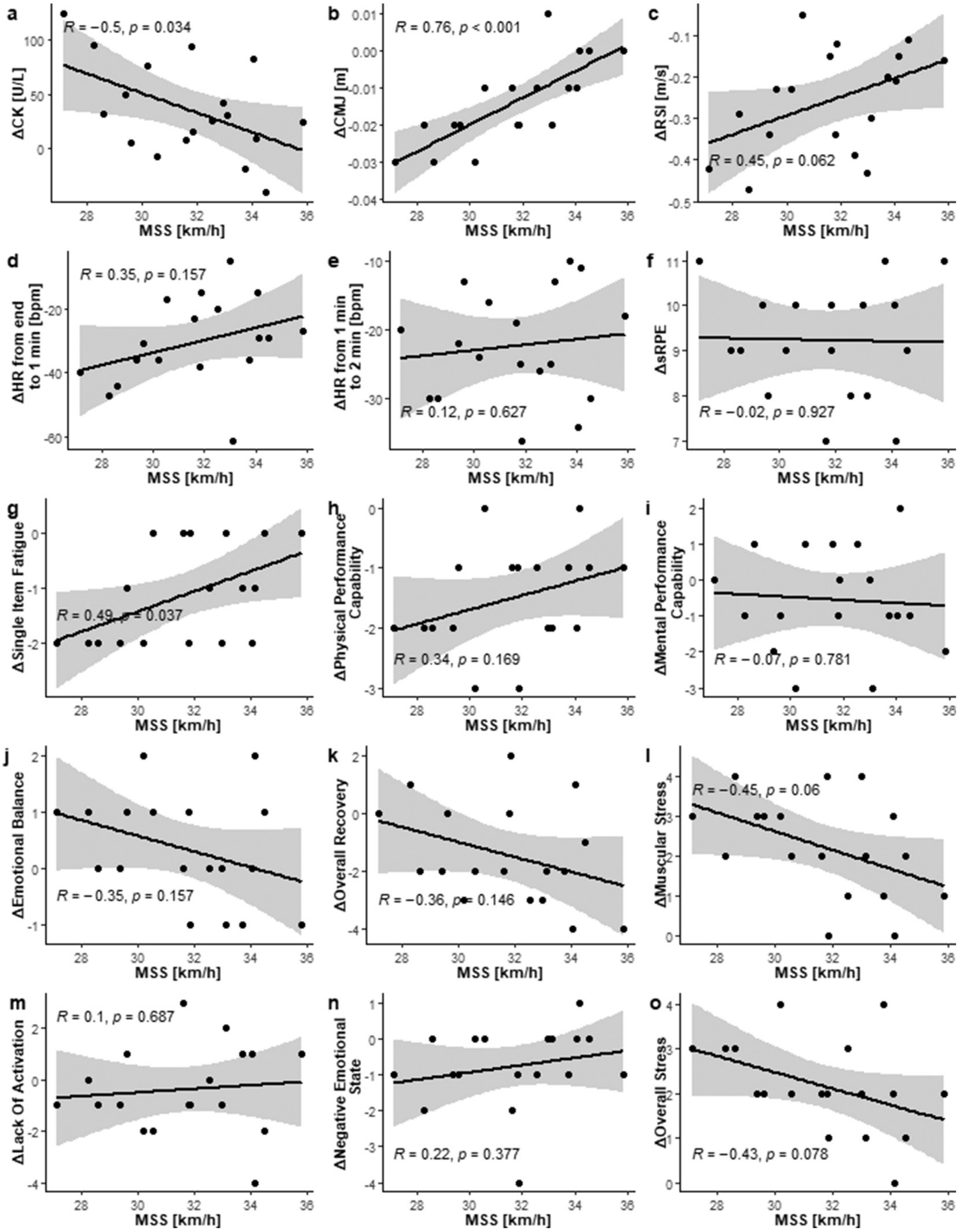

Fig. 3. Scatterplots with regression lines and 95 % confidence intervals (gray area) for MSS with the different objective and athlete-reported variables. MSS – maximal sprinting speed; Δ – delta, i.e., pre-post difference; CK – creatine kinase; CMJ – countermovement-jump; RSI – reactive strength index; HR – heart rate; sRPE – session ratings of perceived exertion; r – Pearson's r; p – significance value.

Recovery, Muscular Stress, and Overall Stress showed higher increases in athletes with a lower ASR compared to a higher ASR and %ASR (but not influenced by $\dot{V}O_{2max}$, MAS, or MSS; see Figs. 2, 3, 4, and 5, and Supplementary Fig. 2). Contrary, the emotional state or motivation, as captured by variables such as Emotional Balance or Lack of Activation, did not show differences in the changes from pre to post HIIT between athletes with higher or lower ASR. An explanation could be that despite high perceived fatigue and stress, the highly-trained athletes can keep their motivation high due to their overall intrinsic motivation, goal setting, or mental resilience. Interestingly, all athlete-reported responses returned to baseline after 24 h (see Supplementary Fig. 1 and Supplementary Table 3). Overall, it seems that different types of runners, i.e., speed-oriented (higher ASR and MSS) or endurance-oriented (higher MAS, lower ASR) runners, experience differences in acute perceived fatigue or recovery after a HIIT, while their emotional state or motivation remains similar. Additionally, their perceived fatigue or recovery returned to the initial level, indicating similar athlete-reported outcome measures related to fatigue and recovery in the longer term between athletes with different ASR types.

4.4. Limitations and future studies

Although our results point toward one direction, examining sex-specific differences in responses to HIIT could provide further

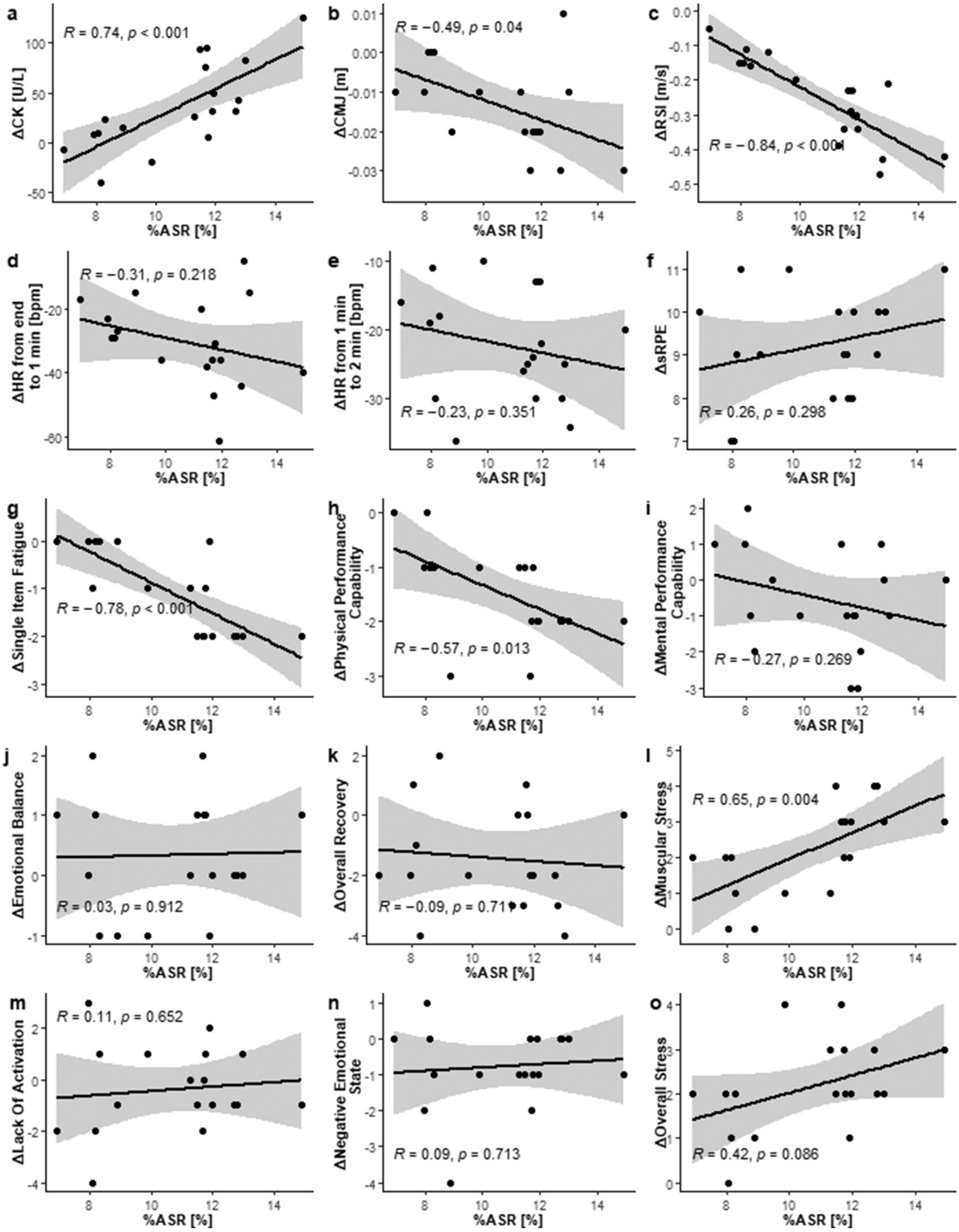

Fig. 4. Scatterplots with regression lines and 95 % confidence intervals (gray area) for %ASR with the different objective and athlete-reported variables. %ASR – percentage of anaerobic speed reserve, i.e., relative intensity of high-intensity interval training; Δ – delta, i.e., pre-post difference; CK – CREATINE kinase; CMJ – countermovement-jump; RSI – reactive strength index; HR – heart rate; sRPE – session ratings of perceived exertion; r – Pearson's r; p – significance value.

understanding, given potential differences in ASR and acute responses.[13,34,35] Due to our rather small sample size, we did not include analyses regarding sex differences in this study; however, a sub-analysis using a Student's *t*-test did not show any differences between sexes regarding the pre/post differences of the acute response. Further investigations should be addressed by future research. While locomotor profiling based on the SRR is additionally suggested due to potential benefits of normalization the absolute value of ASR (i.e., MAS and MSS),[36] we did not look into relationships of the pre/post differences with the SRR because our data did not meet the prerequisites for calculating ratios, i.e., the regression of the numerator and denominator should intersect with the origin and the correlation of the denominator with the ratio should result in a zero correlation.[37] Although, an inclusion criterion for the study has been that the athletes are used to HIIT, differences in the frequency or design of HIIT during their training might influence the athletes' tolerance to the short-format HIIT. Given the small number of studies determining acute athlete-reported responses to HIIT related to locomotor profiles, this research gap also needs to be filled with future studies. Although, we could already provide some insights into the behavior of delayed athlete-reported outcome measures related to fatigue, stress, and recovery after HIIT, i.e., after 24 h, longitudinal investigations of objective and athlete-reported responses to external load are necessary to understand possible long-term differences in load mechanisms related to the locomotor profiles.[4]

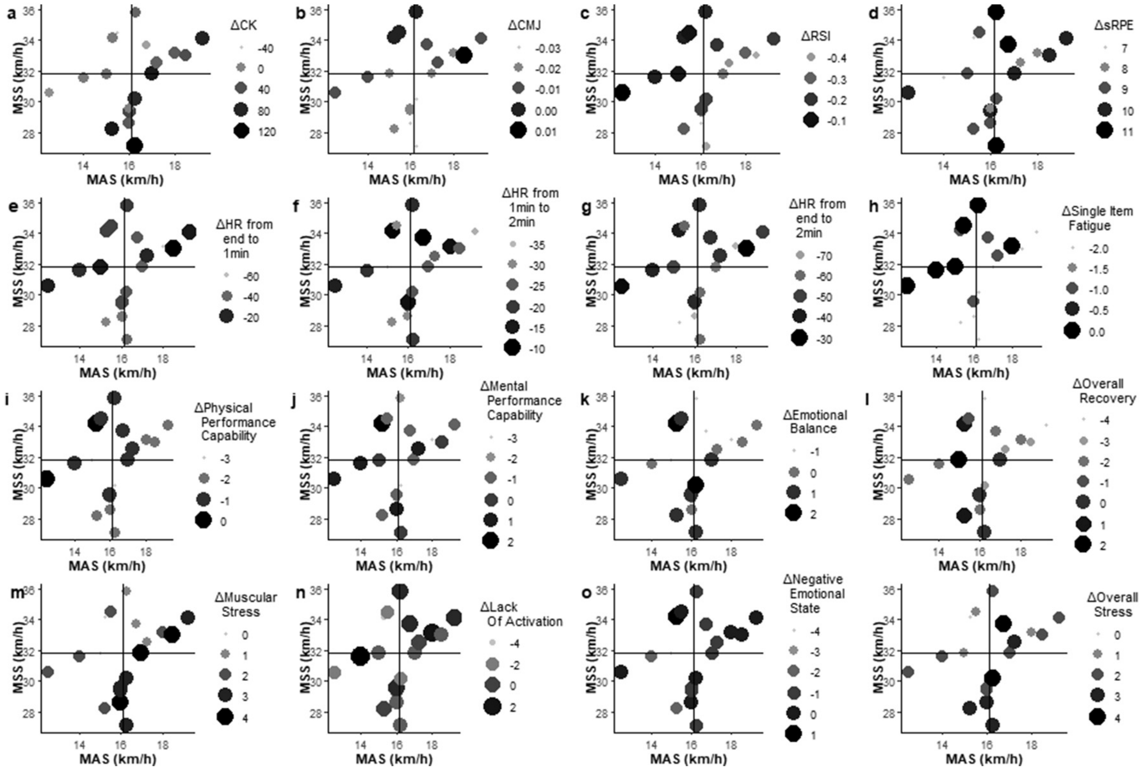

Fig. 5. Scatterplots for the descriptive comparison of MAS and MSS with the pre/post differences of the objective and athlete-reported variables. The vertical lines represent the median of MAS and the horizontal lines the median of MSS. The size and color of the dots indicate the amount of change from pre to post of the respective response variable. MAS – maximal aerobic speed; MSS – maximal sprinting speed; Δ – DELTA, i.e., pre/post difference; CK – creatine kinase; CMJ – countermovement-jump; RSI – reactive strength index; HR – heart rate; sRPE – session ratings of perceived exertion.

5. Conclusions

In conclusion, our results underscore the importance of considering an athlete's ASR (as well as MAS and MSS) leading to different %ASR during HIIT in understanding acute responses to MAS-based HIIT by indicating higher biochemical and neuromuscular responses, and athlete-reported measures for fatigue in athletes with a lower ASR and MSS, compared to athletes with a higher ASR and MSS. However, the HIIT led to similar cardiorespiratory responses, i.e., t90%HR$_{max}$ and t90%$\dot{V}O_{2max}$, during the HIIT in runners with different ASR. Athletes with a higher ASR might benefit from using lower proportions of their ASR during high-intensity exercise to bear higher intensities with a lower internal load than athletes with a lower ASR. These findings can provide implications for optimizing training strategies to for example avoid overload.

CRediT authorship contribution statement

Maximiliane Thron: Conceptualization, Methodology, Software, Formal analysis, Investigation, Project administration, Resources, Writing – original draft, Visualization. **Ludwig Ruf:** Methodology, Software, Formal analysis, Writing – review & editing. **Martin Buchheit:** Resources, Writing – review & editing. **Sascha Härtel:** Methodology, Formal analysis, Writing – review & editing. **Alexander Woll:** Supervision, Writing – review & editing. **Stefan Altmann:** Methodology, Writing – review & editing, Supervision.

Confirmation of ethical compliance

This study was approved by the local ethics committee (Approval Number: 22-10).

Declaration of Generative AI and AI-assisted technologies in the writing process

No Generative AI or AI-assisted technologies were used during the preparation of this work.

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Declaration of interest statement

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2024.12.012.

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