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How Does Interval-Training Prescription Affect Physiological and Perceptual Responses?

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The purpose of this study was to compare physiological responses and perceived exertion among well-trained cyclists (n = 63) performing 3 different high-intensity interval-training (HIIT) prescriptions differing in work-bout duration and accumulated duration but all prescribed with maximal session effort. Subjects (male, mean ± SD 38 ± 8 y, VO_{2peak} 62 ± 6 mL · kg^{-1} · min^{-1}) completed up to 24 HIIT sessions over 12 wk as part of a training-intervention study. Sessions were prescribed as 4 × 16, 4 × 8, or 4 × 4 min with 2-min recovery periods (8 sessions of each prescription, balanced over time). Power output, HR, and RPE were collected during and after each work bout. Session RPE was reported after each session. Blood lactate samples were collected throughout the 12 wk. Physiological and perceptual responses during >1400 training sessions were analyzed. HIIT sessions were performed at 95% ± 5%, 106% ± 5%, and 117% ± 6% of 40-min time-trial power during 4 × 16-, 4 × 8-, and 4 × 4-min sessions, respectively, with peak HR in each work bout averaging 89% ± 2%, 91% ± 2%, and 94% ± 2% HR_{peak}. Blood lactate concentrations were 4.7 ± 1.6, 9.2 ± 2.4, and 12.7 ± 2.7 mmol/L. Despite the common prescription of maximal session effort, RPE and sRPE increased with decreasing accumulated work duration (AWD), tracking relative HR. Only 8% of 4 × 16-min sessions reached RPE 19–20, vs 61% of 4 × 4-min sessions. The authors conclude that within the HIIT duration range, performing at "maximal session effort" over a reduced AWD is associated with higher perceived exertion both acutely and postexercise. This may have important implications for HIIT prescription choices.

Keywords: perceived exertion, session RPE, training load, endurance athletes, cycling

It is generally accepted that successful endurance athletes must balance a large overall training frequency and volume of training with regular exposure to demanding high-intensity interval-training sessions (HIIT), characterized by repeated work bouts in the 85% to 100% VO_2max range. HIIT sessions are typically prescribed as a fixed number of repetitions of a given duration/distance, separated by fixed recovery periods (eg, 4 × 8 min, 2-min recovery). The work bout duration, recovery period, and accumulated work duration (AWD) of a HIIT prescription all have independent influences on physiological responses.[1–3] We have previously suggested that an athlete's execution of an interval training prescription can be likened to solving for the unknown value in an algebraic equation; work bout duration, rest period duration, and accumulated work duration are known values and average work intensity is the unknown value "solved for" by the athlete.[1–3] HIIT sessions often approximate a maximum training effort. The motivated athlete's solution of the interval-training prescription is a pacing process guided by perception of effort during work periods and perception of recovery during rest periods.

Others and we have recently compared different HIIT work intensity × AWD combinations, as well as the effect of the meso-cycle sequencing of different HIIT prescriptions.[3–5] Understanding this interaction at a mechanistic, physiological level is desirable to maximize adaptive signaling effects for a given physiological load. However, HIIT also demands that athletes self-impose large perceived-exertion loads. We know relatively little about how different interval-training variables interact and influence the perception of exertion, either acutely during high-intensity work (ie, Borg RPE[6]), or as an exertional imprint of the entire training session (ie, Foster sRPE[7]). Perceptual scales such as RPE and sRPE are now established tools to aid in estimating training load, often in combination with physiological measures.[8] The mediators and mechanisms connecting HIIT training variables and perceptual responses are therefore fundamental to our understanding of the complex construct *training load*. We argue that the both HIIT prescription choices and overall endurance training-intensity-distribution patterns selected by high-performance athletes must strike a balance between adaptive signaling optimization and long-term training-load tolerance.

The aim of this study was therefore to describe and compare physiological and perceptual responses among a large group of trained cyclists to 3 standardized high-intensity-training prescriptions differing largely in work-bout duration and AWD but always prescribed as maximal session effort.

Methods

Design

This study was a well-powered, exposure-order-balanced, repeated-measures comparison of physiological and perceptual responses to 3 different interval-training prescriptions performed 2 or 3 times weekly over 12 weeks. The current study was part of a 12-week, multicenter, randomized training-intervention study recently described in detail.[5] Details of standard testing procedures and instrumentation have been described previously in our companion paper.[5]

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Subjects

Sixty-nine male cyclists (38 ± 8 y, VO_{2peak} 62 ± 6 $mL \cdot kg^{-1} \cdot min^{-1}$) were recruited to the study using announcements in social media and through local cycling clubs. All subjects were categorized as well-trained[9] or at performance level 4 based on DePauw et al.[10] The study was approved by the ethics committee of the Faculty for Health and Sport Science, University of Agder, and registered with the Norwegian Social Science Data Services. All subjects gave verbal and written informed consent before participation. Initially, 69 subjects completed the study. However, 6 subjects were excluded from the final data analysis due to failure to perform posttesting, or failure to complete >70% of prescribed HIIT (work, illness, injury). Reported data are therefore based on N = 63.

HIIT Sessions

Over 12 weeks, each subject was prescribed 24 supervised HIIT sessions, in addition to laboratory testing, and self-organized ad libitum low-intensity training (LIT) equal to the subject's normal LIT volume. All HIIT was performed indoors as supervised group training sessions, and included a 20- to 30-minute warm-up (55–70% HR_{peak}) and 10- to 30-minute low-intensity (55–70% HR_{peak}) cooldown. Subjects were prescribed the following interval sessions:

- 4 × 4 minutes, with 2-minute recovery periods
- 4 × 8 minutes, with 2-minute recovery periods
- 4 × 16 minutes, with 2-minute recovery periods

The periodization models compared were balanced, such that the different HIIT prescriptions were evenly distributed across time. We also followed typical "3-week build, 1 week easy" periodization over three 4-week mesocycles. Accumulation of fatigue was not detected at the group level over the 12-week training period.[5]

Interval sessions were performed on each subjects own road-racing bicycle mounted on identical Computrainer laboratory ergometers (RacerMate, Seattle, WA, USA) calibrated according to manufacturer specifications and connected to a central PC running dedicated software (PerfPRO Studio, Hartware Technologies). Each subject used the same ergometer throughout the 12-week period. Subjects could adjust cycling load electronically with ±3 W precision, and were provided continuous feedback regarding power, cadence, HR, and elapsed time on a large video screen. During interval sessions, subjects were instructed to cycle at their maximal sustainable intensity during all 4 interval bouts (isoeffort)[1–5] such that they completed the prescribed session structure with even or slightly progressive power from first to fourth interval bout. Mean power, HR (mean and peak), rating of perceived exertion (RPE 6–20),[6] and cadence were quantified at the end of each of the 4 interval bouts of a HIIT session. Blood lactate concentration [la^-] was measured randomly among a subset of 56 subjects at the end of the third and fourth interval bout during different sessions. Overall perceived exertion for the entire training session (sRPE) was reported 30 minutes after the conclusion of each HIT session.[7]

Physiological responses to the 3 HIIT prescriptions are indexed to baseline values for HR_{peak}, VO_2peak, calculated minimum power output eliciting VO_2max (MAP), power at 4-mM blood lactate concentration ($Power_{4mM}$) based on testing procedures previously described.[5]

Statistical Analyses

Data were analyzed using SPSS 22.0 (SPSS Inc, Chicago, IL, USA) and are presented as mean ± SD. Each subject performed up to 8 sessions with the same prescription (4 × 4, 4 × 8, 4 × 16 min) and up to 24 HIIT sessions in total. For comparisons across HIIT prescription, individual responses to a given prescription were therefore calculated as the mean responses for all completed sessions of the same prescription, and summary data are presented as the mean of means (SD) for all 63 subjects. A GLM repeated-measures model (ANOVA) was used to compare physiological and perceptual responses to the 3 HIIT prescriptions. The chi-square test was used to compare power-pacing distributions in response to the 3 prescriptions. One-way ANOVA was used to compare RPE responses in subgroups with different overall power-pacing outcomes. For all comparisons, statistical significance was accepted as $\alpha \leq .05$.

Results

Physiological and perceptual responses to the 3 different HIIT prescriptions are presented in Table 1. Both mean HR and peak HR increased modestly but significantly for each 50% reduction in work-bout duration. Blood lactate responses were markedly different across prescriptions, with blood lactate concentration at the end of the 4 × 16-minute sessions approximating maximal lactate steady-state (MLSS) values typical for cycling[11] and values at the end of 4 × 4-minute sessions approaching those seen during maximal-exercise testing. Despite the same maximal session effort, both RPE averaged over 4 interval bouts, and sRPE, were significantly different across prescriptions. As Table 1 shows, the 4 × 4-minute interval prescription was 4 to 6 times more likely to elicit near-maximal RPE (19 or 20 on the Borg 6–20 scale) and sRPE (9 or 10 on the Foster 0–10 scale) in these well-trained subjects.

The evolution of power output, heart rate, and RPE during the 3 interval sessions is summarized in Figure 1. In keeping with the instructions given to subjects, power output was maintained relatively constant over the 4 interval bouts (panel A). In contrast, both heart rate (HR, panel B) and RPE (panel C) increased constantly throughout the interval session. RPE could also be seen to track HR responses (Figure 2). In contrast, when comparing physiological and perceptual responses after each of the 4 work intervals within the 3 prescribed sessions, RPE appeared largely independent of differences in elapsed work time, relative power output, or blood lactate concentration per se (Table 2).

Compliance with the power-pacing recommendations was not 100% and individual variation in power distribution was observed. Subjects were found to more often fail to comply with the power pacing instructions when performing the highest intensity 4 × 4 minute HIT session (Figure 3). We averaged all completed sessions (~7–8) of each HIT prescription to quantify a typical interval-session pacing pattern for each subject. Individual patterns were categorized as even pacing if the fourth bout was performed at 98% to 102% of first-bout power. Performance of the fourth bout at >102% of first-bout power was categorized as increasing power. Performance of the fourth bout at <98% of the first-bout power was categorized as decreasing power.

RPE responses in subgroups achieving different power pacing outcomes are compared for each interval prescription in Figure 4, panels A–C. The relatively few athletes (n = 6) who showed a decreasing power development over 4 × 16 minutes tended to have elevated RPE for the entire session, but this tendency was not statistically significant (Figure 4 panel A). RPE responses during

Table 1 Physiological and Perceptual Responses During Interval Sessions Executed as 4 × 16, 4 × 8, and 4 × 4 Minutes During a 12-Week Intervention Period (N = 63 Subjects)

	4 × 16 min	4 × 8 min	4 × 4 min	*P**
Sessions completed (n)	469	486	466	
Power (W)§	276 (25)	308 (29)	342 (33)	<.001
Power (W/kg)§	3.5 (0.4)	3.9 (0.4)	4.3 (0.4)	<.001
% Peak power output§	65 (4)	71 (4)	80 (4)	<.001
% $Power_{4mM}$§$	97 (8)	106 (8)	118 (9)	<.001
% power 40-min time trial§$	95 (5)	106 (5)	117 (6)	<.001
Blood lactate (mMol·L-1)#	4.7 (1.6)	9.2 (2.4)	12.7 (2.7)	<.001
HRmean, work bouts (%HRpeak)§	86 (3)	88 (2)	89 (2)	<.001
HRpeak, work bouts (%HRpeak)§	89 (2)	91 (2)	94 (2)	<.001
RPE (Borg 6–20 scale)	15.0 (1.1)	16.2 (0.8)	17.1 (0.9)	<.001
% sessions with RPE_{peak} 19–20	8.4	26.8	60.9	<.001
sRPE (Foster 1–10 scale)	6.3 (1.0)	6.9 (1.0)	7.7 (1.2)	<.001
% sessions with sRPE 9–10	5.3	7.8	32.4	<.001

Note: All values are calculated as the mean of means (SD) of up to 8 training sessions for each interval prescription in 63 subjects.

§All values of power, mean, and peak heart rate (HR) and rating of perceived exertion (RPE) are mean (SD) of all 4 work bouts. Session RPE (sRPE) was quantified 30 min postexercise.

$Reference values for $Power_{4mM}$ blood lactate are mean of 4 tests performed at pre, 4, 8, and post during the 12-wk training period. Reference value for 40-min time-trial power is mean of pre- and posttest results.

#Blood lactate was sampled randomly among a subset of 56 subjects after work bouts 3 and 4, and a total of 531 samples (~10 per participant) were collected.

*One-way repeated-measure ANOVA. All 3 conditions were significantly different from each other.

the 4 × 8-minute prescription were not clearly differentiated across pacing subgroups (Figure 4 panel B). In contrast, among the 23 of 63 subjects who typically had to reduce their power output relative to starting levels by the end of 4 × 4-minute sessions, RPE was elevated in the first 3 bouts before converging with other power pacing subgroups by the end of the fourth bout (Figure 4, panel C).

Discussion

This investigation provides unique insights into how the key prescription variables of a HIIT session influence perceived exertion. Based on physiological and perceptual data collected on >1400 HIIT sessions, our key finding is that acute work intensity drives RPE and session RPE amplitude much more strongly than accumulated work duration during an interval session over the range compared. Average RPE was consistently higher (by ~2 RPE units) and subjects were ~7 times more likely to essentially "max out" the RPE scale (RPE 19–20) when performing 4 × 4-minute intervals compared with 4 × 16 minutes, despite the same instructions and encouragement to give a maximum session effort. Similarly, subjects reported higher sRPE after the much shorter interval sessions performed at higher work intensity, and were ~6 times more likely to report a 9 or 10 for sRPE after 4 × 4 than 4 × 16-minute sessions. These findings have important practical implications for training prescription. A second key finding was that the prevailing relative heart rate and its development during the training session was more strongly associated with acute RPE and session RPE than other variables such as power output, total work duration, or even blood lactate concentration. This finding informs recent studies and discussions regarding how different neurological information streams ultimately drive the brain's perception of exertion during exercise.

We prescribed HIIT training sessions using an "isoeffort" model that we believe is most consistent with the daily practice of endurance athletes. In this model, we do not attempt to prescribe sessions with equivalent work (isoenergetic matching), as this is an experimental design with no basis in actual training practice among endurance athletes. In our isoeffort model, the training variables impose different constraints on achievable work intensity and physiological characteristics of each session prescription (eg, blood lactate and intensity zones), but the athlete's overall exertion or session effort during the different sessions is assumed to be equivalent. Previously, we observed statistically equivalent RPE amplitude and development patterns in runners performing isoeffort HIIT sessions with different work-bout duration or rest-period duration but equivalent AWD.[1,2] The specific sessions prescribed (4 × 4, 4 × 8, and 4 × 16 min) here were chosen based on a previous investigation,[3] as well as descriptive data from high performance endurance athletes detailing typical training sessions.[12,13] The present data confirm our preliminary findings from a smaller between-groups comparison[3] and suggest that the same session effort does not correspond to equivalent RPE and session RPE endpoints for different HIIT prescriptions. Equivalent session effort need not result in equivalent perceived exertion during, at the end of, or 30 minutes after different HIT prescriptions. Instead, our data suggest an effort-distribution strategy involving some integration of the acute perception of exertion and the duration over which that level of exertion can be mobilized or tolerated.

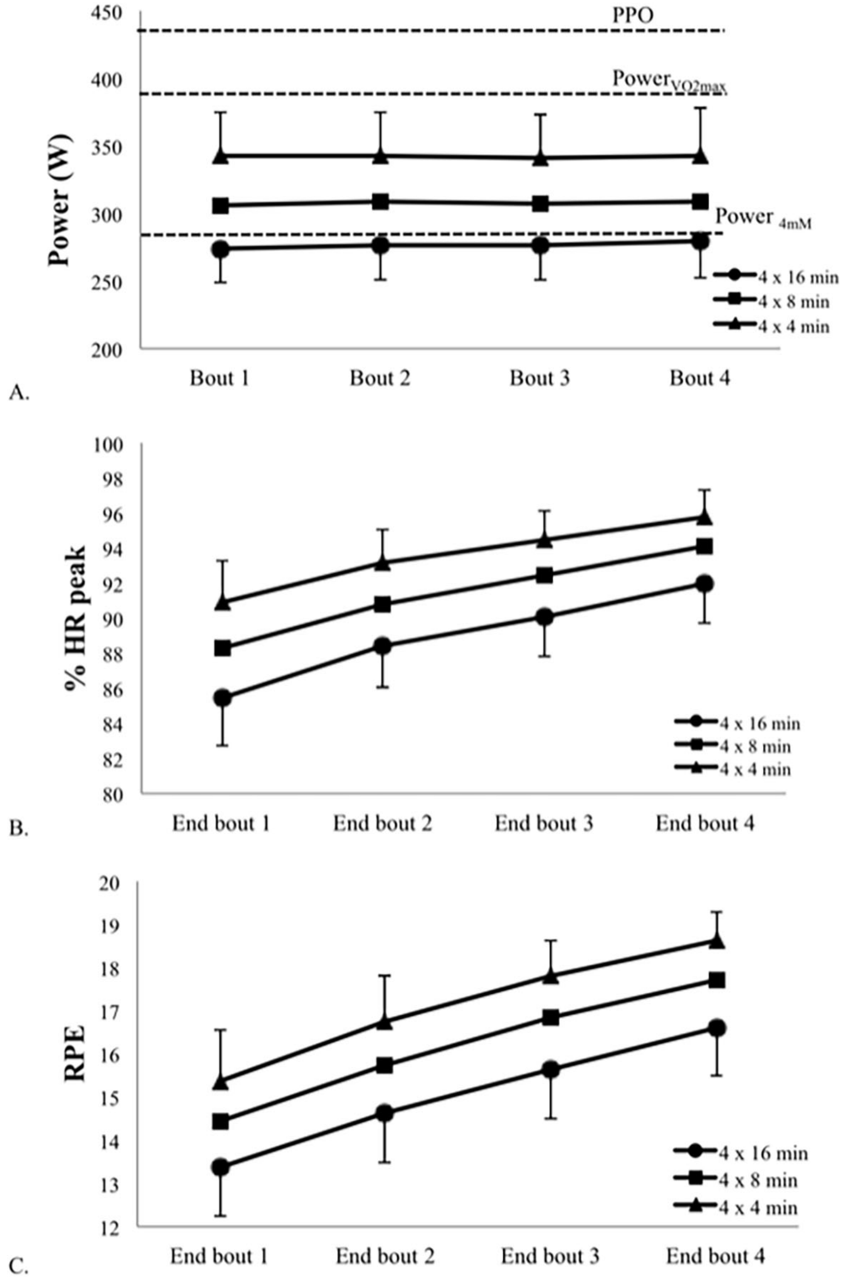

Figure 1 — Evolution of power output, heart rate, and RPE during interval sessions. Error bars represent standard deviation of the mean. Error bars are omitted from 4 × 8-minute data for clarity but are of the same magnitude as 4 × 4- and 4 × 16-minute conditions. Power output was significantly different ($P < .001$) between the 3 interval prescriptions at all time points but not significantly different across work bouts. For HR and RPE, all points were statistically different between interval prescriptions and across work bouts, $P < .001$.

These physiological and perceptual data reinforce the important fact that there is large variation within a range of training prescription labeled as "high intensity interval training" where heart rate is a relevant physiological indicator for work intensity. Average HR for an accumulated duration of 64 minutes (4 × 16 min) was 86% ± 3% of HR_{peak}. When AWD was reduced to 16 minutes (4 × 4 min), average HR during work bouts only increased to 89 ± 2% HR_{peak}. This small HR difference coincided with much larger differences in power, blood lactate concentration, and RPE, reinforcing the argument that great care must be taken when using HR to guide interval training within the high-intensity work range. Using peak HR at the end of each interval work bout as an intensity indicator probably gives increased sensitivity, based on the present data (Table 2).

RPE may be an important supplement to, or even a replacement for HR when guiding the pacing of hard interval training sessions. Our data give reasonable guidelines for both the starting RPE that should be targeted for a given interval prescription, and the likely progression of perceived exertion to the last work bout. With increasing accumulated work duration of HIIT, the starting RPE target should be lowered. In the current study, RPEs of 13 to 14, 14 to 15, and 15 to 16 were typical exertion levels after the first work bout of the 4 × 16-, 4 × 8-, and 4 × 4-minute prescriptions, respectively. Independent of starting RPE, perceived exertion typically increased by about 3 units to end at 16 to 17, 17 to 18, and 18 to 19 for accumulated work durations of 64, 32, and 16 minutes, respectively. It is interesting to note that a decreasing power output profile, or "power pacing failure," was most often observed during the shortest interval bouts. It appears that when athletes initially overestimated their capacity and effort during the 4 × 4 session, they were often unable to absorb the pacing error and maintain even power. Perceptually, the magnitude of this pacing error could be retrospectively identified as an RPE during the first bout 1 to 2 units above that observed with even or increasing power pacing (Figure 4, panel C).

Figure 2 — RPE–heart rate relationship across interval session prescriptions and work bouts. The 12 points in the figure represent grand means of 63 individual mean values from the 12 different session-type × bout-number combinations generated by the 3 interval training prescriptions. Standard deviations are omitted from the figure for clarity but are presented in Table 2. Pearson *r* = .988.

At a more mechanistic level, why do we observe that despite giving a maximal session *effort* for all 3 interval prescriptions, subjects consistently reported near-maximal *exertion* (19 to 20 RPE) only at the end of the shortest interval sessions? One partial explanation is that this was hard training, but not racing. In a race, it seems likely that these subjects would have often attempted to mobilize a finishing sprint. This final exertion would be expected to elevate the end RPE, and perhaps also the reported session RPE in these longer sessions. However, the lack of a finishing sprint during training sessions cannot explain the robust RPE differences observed across interval bouts for the different prescriptions.

A second issue is the difficult distinction between effort and exertion. Abbiss et al[15] recently argued that research around perceived exertion is complicated by the frequent mixing of these terms in both definitions and instructions for use of RPE and other perceptual scales. Exertion has been defined as "the degree of heaviness and strain experienced in physical work."[14(p8)] In contrast, effort has been described as "the amount of mental or physical energy given to a task."[15(p1236)] Accepting these distinctions, we propose that a maximal mental or physical effort can be elicited when mobilizing high but submaximal exertion over an extended period, or near-maximal exertion over a much shorter duration. That is, effort ≈ exertion amplitude × exertion duration. Based on the present data, we argue that maximal session effort during intensive exercise can be

Table 2 RPE in Relation to Duration, Power, and Physiological Characteristics of Work Bouts

RPE (SD)	$\%HR_{peak}$ (SD)	Session type	Bout #	Accumulated duration	Power (W)	Power (% 4mM)	La^{-}* (mol/L)
13.3 (1.1)	85.3 (2.9)	4 × 16	1	16	274	94.6	na
14.4 (0.9)	88.1 (2.2)	4 × 8	1	8	306	105.7	na
14.6 (1.1)	88.3 (2.5)	4 × 16	2	32	276	95.3	na
15.3 (1.2)	90.6 (2.6)	4 × 4	1	4	342	118.3	na
15.6 (1.1)	89.9 (2.4)	4 × 16	3	48	276	95.5	4.6
15.7 (0.8)	90,7 (1.9)	4 × 8	2	16	308	106.5	na
16.6 (1.1)	91.6 (3.1)	4 × 16	4	64	279	96.3	5.0
16.7 (1.1)	92.9 (2.0)	4 × 4	2	8	343	117.7	na
16.8 (0.7)	92.4 (1.8)	4 × 8	3	24	307	106.3	8.8
17.7 (0.8)	94.0 (1.9)	4 × 8	4	32	309	106.7	9.8
17.8 (0.8)	94.2 (1.8)	4 × 4	3	12	340	118.2	12.2
18.6 (0.7)	95.7 (1.7)	4 × 4	4	16	339	118.1	13.2

Mean (SD) values are calculated as mean (SD) of individual mean responses for up to 8 sessions in 63 subjects. Grouped data among the 12 unique work bout conditions show similar rating of perceived exertion (RPE) and heart rate (HR) responses despite markedly different work duration, power output, and blood lactate concentration.

*Blood lactate samples were only collected during the third and fourth bouts of interval sessions.

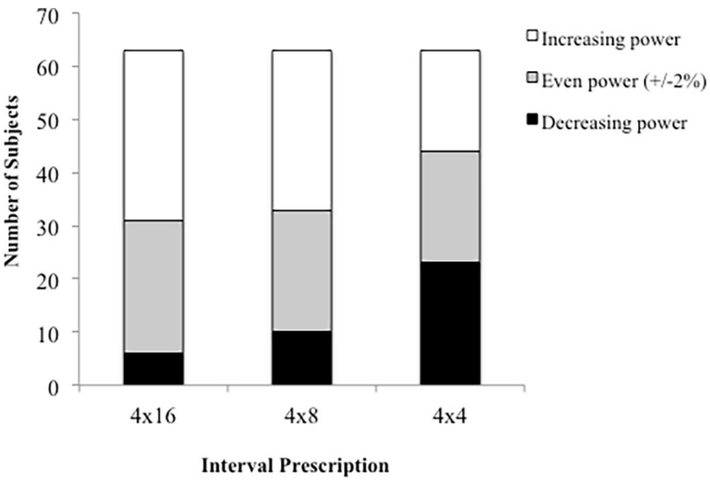

Figure 3 — Pacing distribution among 63 trained subjects performing 3 different HIT prescriptions. For the increasing-, even-, and decreasing-power groups, fourth-bout powers were approximately 104% ± 2%, 100% ± 1%, and 95% ± 2% of first-bout power for each interval prescription, respectively. The pacing-outcome distribution across interval prescriptions was significantly different ($P < .01$).

likened to the mental cost integral associated with maintaining some level of physical exertion over a given duration. Effort describes a capacity with interdependent amplitude (acute exertion) and duration (sum of work bouts) components. This proposed distinction between effort and exertion is consistent with our present data. It is also consistent with concepts proposed by Abbiss et al[15] explaining why subjects are often unable to reach maximal exertion when performing different exercise tasks.

Finally, these data can be examined in light of several different models attempting to explain the relationships between physiological systems and the brain. In their recent review, Abbiss et al[15] identify 7 different models from the literature explaining these relationships. One key point of debate among supporters of different models is whether afferent feedback from peripheral sensors directly influences perceived exertion during exercise, or whether perceived exertion is centrally driven and not directly modulated by this peripherally derived neural information. Based on the strong correlation between relative heart rate (assumed to be a corollary of central motor command) and RPE in the present data, combined with the observation that other potential modulators of afferent feedback such as power output, blood lactate concentration, and elapsed duration of exertion were not strongly correlated with RPE, we propose that the present data are most consistent with models proposing a feed-forward mechanism where central drive is the key mediator of perceived exertion.[16,17]

While our data provide a unique and robust comparison of 3 standardized HIIT prescriptions, there are important limitations to this study. High intensity interval training comprises a nearly unlimited number of combinations of work duration, recovery duration, and total work. Therefore, while we believe the present data have general relevance to other HIIT prescriptions, care should be taken in extrapolation to other HIIT models. It is also important to distinguish different intensity domains encompassed by the cyclic work-rest, interval-training structure. We cannot extend the present findings to sprint interval training (SIT) involving very short, very high intensity work bouts. Other studies are needed to examine how RPE responds to different SIT prescriptions. It is also important to recognize the individual character of the RPE-intensity relationship

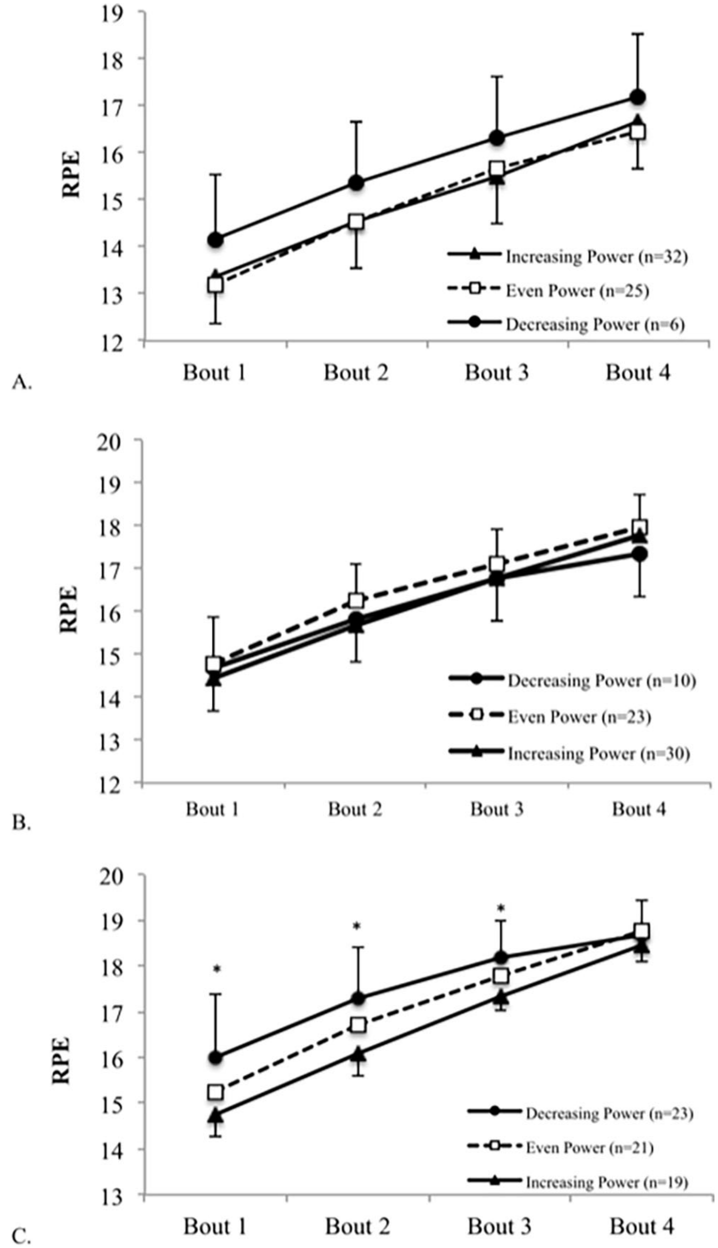

Figure 4 — RPE responses during HIT sessions with 4th:1st-bout power ratios categorized as decreasing power (<98%), even power (98–102%), or increasing power (>102%). Panel A: 4 × 16 minutes. Panel B: 4 × 8 minutes. Panel C: 4 × 4 minutes. *$P < .005$, RPE for decreasing-power group versus other groups.

and its interpretation. RPE and sRPE are ordinal scales with verbal anchors, although we generally treat both as ratio scales. A 16 on the RPE scale or 8 on the sRPE scale is not a directly comparable quantity across athletes. Like HR, individual calibration of exertion scales is important to ensure effective use of RPE and sRPE as training monitoring tools.

Practical Applications

Here, we provide endurance athletes and coaches with a practical framework for guiding HIIT prescriptions based on expected relative power and intensity outcomes. Given the challenges of using heart rate monitoring during HIIT training associated with response lag time, drift, and sensitivity to environmental conditions, the present data also provide coaches with alternative RPE based guidelines that can be useful when prescribing HIIT. On a practical level, we must caution the direct interpretation of training-load contribution from HIIT sessions as sRPE × accumulated work duration (min).[7,18] In the HIIT range explored here, these calculations assign very large differences in training load contribution to different session prescriptions (eg, 64 min × sRPE 7 = 448, vs 16 min × sRPE 9 = 144) that are opposite of sRPE and RPE tendencies, as well as anecdotal report. We are unable to reconcile these calculations with subject perceptions,[3,5] athlete fatigue,[3] or training outcomes from 2 large training studies.[3,5] sRPE is a very practical, easily acquired, global indicator of training exertion that matches reasonably well with physiological markers.[8,19] However, we challenge athletes, coaches and scientists to further explore how the magnitude and duration of exertion fit together when estimating training load across different intensity-duration combinations used in high-intensity interval training.

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