

Supramaximal Training and Postexercise Parasympathetic Reactivation in Adolescents

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ABSTRACT

BUCHHEIT, M., G. P. MILLET, A. PARISY, S. POURCHEZ, P. B. LAURSEN, and S. AHMAIDI. Supramaximal Training and Postexercise Parasympathetic Reactivation in Adolescents. *Med. Sci. Sports Exerc.*, Vol. 40, No. 2, pp. 362–371, 2008. Repeated supramaximal exercise training is an efficient means of improving both aerobic and anaerobic energy system capacities. However, the influence of different levels of supramaximal training on parasympathetic function is unknown. **Purpose:** To compare the effects of repeated-sprint (RS) versus high-intensity intermittent training (HIT) on performance and postexercise parasympathetic reactivation in trained adolescents. **Methods:** Fifteen male adolescents (15.6 ± 0.8 yr) were divided into two groups that performed 9 wk of either RS (repeated all-out 6-s shuttle sprints; 14–20 s of recovery; $N = 8$) or HIT (15- to 20-s runs at 95% of the speed reached at the end of the 30–15 intermittent fitness test (V_{IFT}); 15–20 s of recovery; $N = 7$). Groups performed intervals twice per week and maintained similar external training programs. Before and after training, performance was assessed by the V_{IFT} , countermovement jump (CMJ), 10-m sprint time (10 m), mean RS ability time (RSA_{mean}), and heart rate (HR_{sub}) level during a 6-min submaximal (60% V_{IFT}) exercise test, where parasympathetic reactivation was assessed during the recovery phase (i.e., HR recovery time constant ($HRR\tau$) and HR variability (HRV)). **Results:** Parasympathetic function, V_{IFT} , and RSA_{mean} were improved with HIT but not RS training. In contrast, changes in CMJ and HR_{sub} were similar in both groups. A significant relationship was shown between the decrease in $HRR\tau$ and RSA_{mean} ($r = 0.62$, $P < 0.05$; $N = 15$). **Conclusion:** HIT was more effective than RS training at improving postexercise parasympathetic function and physical performance. In addition, $HRR\tau$, which was more sensitive to training than HRV indices, seems to be a useful performance-related measurement. **Key Words:** HEART RATE VARIABILITY, HEART RATE RECOVERY, HIGH-INTENSITY INTERVAL TRAINING, REPEATED-SPRINT ABILITY

Sympathetic hyperactivity or reduced cardiac vagal tone after exercise are associated with increased risk of cardiovascular disease; a low parasympathetic activity may underlie ischemic heart disease and the pathogenesis of malignant ventricular arrhythmias or sudden cardiac death (3,28). Regular participation in aerobic activities not only increases fitness level (29) but also improves resting and postexercise cardiac parasympathetic function (3). It is now believed that most children and adolescents of today's industrial societies are receiving low levels of physical activity, which leads to an increased risk of cardiovascular and other lifestyle-related diseases in

adulthood (14). Therefore, exploration of the impact that specific exercise training regimens have on adolescent physical capacities and cardiovascular function may improve our ability to lower cardiovascular disease risk in adulthood through appropriate exercise training prescription in the early years.

Although views concerning ways by which we should optimally prescribe training (in terms of exercise mode, intensity, and volume) differ (14,20,23), the time-efficient potency of high-intensity exercise training for improving health-related indices of physical fitness and performance is remarkable (17). Studies have shown that varying forms of high-intensity interval training are effective at improving various components of physical fitness in adults (17,20,23,24) and in young individuals (2,26). Nevertheless, to the best of our knowledge, no study has ever investigated the effect of supramaximal training (i.e., at an intensity higher than that associated with maximal oxygen uptake) in adolescents. In fact, it has been suggested that children and adolescents may be "physiologically advantaged" to perform supramaximal intermittent exercises, because they have a greater ability than adults to rapidly recover from intense exercise with their fast oxygen and

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heart rate (HR) kinetics, quicker PCr resynthesis, and more efficient acid/base regulation (13).

The influence that intense training has on parasympathetic function in the young is not clear. In adolescent athletes, an intense training period lasting 5 wk (16) to 5 months (19,25) has been reported to have either no effect (19) or to induce minor improvements in parasympathetic modulation (16,25). In contrast, we recently have shown that participation in intense activity over a moderate level was necessary to observe increases in HR variability (HRV) vagal-related indices (9). In line with previous results in adults (10,21), these findings suggest that exercise intensity may be the most critical aspect of a training program necessary for improving autonomic function. Indeed, it is possible that intensity was not high enough in studies that have reported no change in autonomic function after training (19), and that supramaximal training might thus be particularly efficient at improving parasympathetic activity. We have recently observed in adults an almost abolished beat-to-beat HRV and HR recovery time constant during a 10-min recovery period after two distinct supra-maximal exercise bouts (7). The results suggest that postexercise parasympathetic function was altered to the same extent after an acute bout of repeated all-out 3-s sprints and after high-intensity intermittent 30-s runs (7). However, there was no evidence that these perturbations of parasympathetic reactivation *per se* would constitute stimuli that would influence long-term change in autonomic function. Because differing levels of supramaximal intensity training have yet to be investigated, we sought to compare the long-term effects of two forms of supramaximal exercise training on adolescent physical performance and postexercise autonomic function; a repeated all-out short sprint training program and a 15- to 20-s high-intensity intermittent running regimen. We hypothesized that both 9-wk training regimens would induce equivalent improvements in adolescent parasympathetic reactivation after exercise.

METHODS

Subjects. On the basis of the assumption that a 8 ± 5 bpm difference in HR recovery 60 s after the end of exercise (HRR_{60s}) is meaningful (6,11), we used Minitab 14.1 Software (Minitab Inc, Paris, France) to determine that a sample size of eight subjects per group would provide a statistical power of 0.8 at an alpha level of 0.05. Because of higher standard deviation values, statistical power was estimated to be lower in most HRV indices (i.e., around 0.65 for the root mean square of successive R-R interval differences, RMSSD). Thus, we considered effect size for all analyses (see Statistical analysis paragraph). Seventeen trained male adolescent handball players (15.6 ± 0.8 yr, 178.0 ± 9.1 cm, and 75.8 ± 6.5 kg), who trained 10 ± 2.1 h-wk⁻¹ in a regional center, participated in the study. Their maturational status was estimated at pubertal stage IV

($N = 8$) or V ($N = 9$) according to Tanner classification by an experienced investigator via direct visual observation of primary and secondary sexual characteristics (abdominal, shoulder, chest and facial hair, Adam's apple, and voice). The subjects were all free of cardiovascular and pulmonary disease and were not taking any medications. The study conformed to the recommendations of the Declaration of Helsinki, and participants and their parents gave voluntary written informed consent to participate in the experiment, which was approved by the local institutional research ethics committee.

Experimental overview. Participants were randomly divided into two training groups that performed, at the end of their usual training sessions, either short repeated all-out shuttle sprints (RS, $N = 9$) or high-intensity intermittent running (HIT, $N = 8$). Groups were equally matched for maturation level, and only subjects that participated in all training sessions were included in the analysis. Tests were performed 1 wk before the commencement of training and were repeated in the week after the 9-wk training period (Table 1). Tests included a graded aerobic intermittent test (30–15_{IFT}) (5), countermovement jump (CMJ), 10-m sprint time (10 m), a 4 × 5-m shuttle run test, an RS ability (RSA) test, and a 6-min submaximal (60% of the speed reached at the 30–15_{IFT}, V_{IFT}) running bout, where parasympathetic reactivation was assessed through beat-to-beat HR collection during the 10-min recovery phase. To verify the reliability of HR measurements during and after the submaximal exercise, subjects repeated the 6-min run (plus the 10-min recovery) at 1-wk intervals (W-1 and W0) before their training program under very low training loads. All tests were performed on an indoor synthetic track where ambient temperature ranged from 18 to 22°C. Identically for the three testing sessions (at W-1, W0, and W9), at least 48 h separated each testing session from the preceding training session, and all tests were conducted at the same time of day. Subjects were also asked to maintain their usual diet throughout the study and to have their last meal

TABLE 1. Training program for repeated-sprint (RS) and high-intensity intermittent training (HIT) groups.

	RS	HIT
Week -1	6-min submaximal exercise (reliability test)	
Week 0	Complete physical fitness and parasympathetic function battery test	
Week 1	2 × [2 × (6 × 2 × 15 m (14"p))]	2 × [9 × (20" (90%) - 20"p)]
Week 2	2 × [3 × (5 × 2 × 15 m (14"p))]	2 × [12 × (20" (90%) - 20"p)]
Week 3	2 × [2 × (6 × 2 × 15 m (14"p))]	2 × [15 × (20" (90%) - 20"p)]
Week 4	Regeneration*	
Week 5	2 × [2 × (5 × 2 × 20 m (23"p))]	2 × [14 × (15" (90%) - 15"p)]
Week 6	2 × [2 × (6 × 2 × 20 m (23"p))]	2 × [16 × (15" (95%) - 15"p)]
Week 7	2 × [2 × (5 × 2 × 20 m (23"p))]	2 × [14 × (15" (95%) - 15"p)]
Week 8	2 × [3 × (6 × 2 × 20 m (23"p))]	2 × [24 × (15" (95%) - 15"p)]
Week 9	1 × [1 × (6 × 2 × 20 m (23"p))]	1 × [10 × (15" (95%) - 15"p)]
Week 10	Complete physical fitness and parasympathetic function battery test	

Description of reliability, pre- and posttraining test scheduling, and details of training contents for the 9-wk training period. RS training in week 1 listed as 2 × [2 × (6 × 2 × 15 m (14"p))] refers to two sessions per week, including two series of six, 2 × 15-m shuttle sprints, interspersed with 14 s of passive recovery. Between RS series: 2 min of passive recovery. p, passive; a, active recovery (running at 45% V_{IFT}). * For training contents of regeneration week, please refer to the Methods section.

(with no caffeine ingestion) at least 3 h before the beginning of the testing session.

Training intervention. Subjects performed two supramaximal sets per week (Monday and Wednesday) for three and five consecutive weeks (separated by one “recovery” week). Sets were always completed at the end of the handball training session, after the last technical/tactical drill, and were carefully supervised by the coaches. Except the RS and HIT sets, all other training components were kept similar in both groups (total training time = 9.5 ± 2.1 h·wk⁻¹, including technical, tactical, strength, and speed training). Strength training consisted of about 1 h of weight lifting for the upper and lower limbs (65–85% 1RM). Speed training consisted of two 20-min sessions, including athletic drills, 8–10 standing starts with 3- to 15-m sprints and about 10 in-depth jumps (< 15 cm). The remaining training time was devoted to handball training. Pilot studies conducted before the present study showed that technical and tactical training sessions can be qualified as intermittent, moderate-intensity aerobic exercise (45–75% maximal oxygen uptake for 1–1.5 h). Although handball and complementary training contents were similar each week, supramaximal exercise training programs followed a typical periodized plan to prevent overtraining, and they included a short tapering period to maximize final performance (Table 1). As detailed in Table 1, the RS program consisted of two or three sets of five to six 15- to 20-m shuttle sprints (~100–120% V_{IFT}) interspersed with 14 s of passive or 23 s of active recovery (45% V_{IFT}), whereas the HIT training consisted of one or two sets of 9–24 × 15- to 20-s runs (90–95% V_{IFT}) interspersed with 15–20 s of passive recovery. Because the V_{IFT} is always higher than one’s maximal aerobic velocity (MAV), running at 90–95% of V_{IFT} can be effectively quantified as supramaximal exercise (~120% of MAV) (5). RS and HIT programs were matched for exercise duration at each training session. During the recovery week (week 4; total training time = 2.0 ± 0.1 h·wk⁻¹), athletes were asked to only perform three 40-min Fartlek training runs, where athletes were asked to run at a subjective 6–7 level on a 0–10 Borg scale.

Materials. After application of conductive gel, an electrode transmitter belt (T61, Polar Electro, Kempele, Finland) was fitted to the chest of each subject as instructed by the manufacturer. A Polar S810 HR monitor (Polar Electro, Kempele, Finland) (15) continuously recorded beat-to-beat HR during all tests, as well as during the first and last training session.

HR data treatment. All R–R series recorded by the S810 were extracted on an IBM-compatible PC with the processing program Polar Protrainer 5.1 (Polar Electro, Kempele, Finland). Occasional ectopic beats (irregularity of the heart rhythm involving extra or skipped heartbeats; that is, extrasystol and consecutive compensatory pause) were visually identified and manually replaced with interpolated adjacent R–R interval values.

Maximal graded aerobic test. Maximal aerobic performance for each subject was assessed using a 30–15 intermittent fitness test (30–15_{IFT}) (5). The 30–15_{IFT} consists of 30-s shuttle runs interspersed with 15-s passive recovery periods. This intermittent shuttle field test elicits peak HR, and the reliable final running speed (V_{IFT} ; intraclass correlation coefficient = 0.96) has been shown to be an accurate tool for individualizing intermittent shuttle running exercise (5). For this test, velocity was set at 8 km·h⁻¹ for the first 30-s run, and speed was increased by 0.5 km·h⁻¹ every 30-s stage thereafter. Subjects were required to run back and forth between two lines set 40 m apart at a pace that was governed by a prerecorded beep. The prerecorded beep allowed the subject to adjust their running speed within a 3-m zone placed in the middle and at each extremity of the field. During the 15-s recovery period, subjects walked in the forward direction towards the closest line (at either the middle or end of the running area, depending on where their previous run had stopped); they would start the next run stage from this line. Subjects were instructed to complete as many stages as possible, and the test ended when the subject could no longer maintain the required running speed or when the subject was unable to reach a 3-m zone in time with the audio signal on three consecutive occasions. The velocity (km·h⁻¹) attained during the last completed stage was determined as the subject’s V_{IFT} . The field test was thought to be maximal if the following criteria were met: 1) a maximal HR (HR_{max}) attained within 10 bpm of the age-predicted maximum ($220 - \text{age}$), and 2) volitional fatigue. All subjects met both criteria before and after the 9-wk training period.

Lower-limb explosive power test. Lower-limb explosive strength was indirectly assessed using a vertical CMJ with flight time measured by an Optojump (Ergojump, Globus Italia, Codogno, Italy) to calculate jumping height (CMJ; cm). Because this method of measuring vertical jump height can be biased by some methodological flaws (notably, landing with leg flexion), an experienced investigator validated each trial visually. CMJ was performed three times, separated by 45 s of passive recovery, and the best performance was recorded.

Speed tests. Speed quality was evaluated by a 10-m standing-start run (10 m; s) and a 4 × 5-m shuttle run test (4 × 5 m; s), recorded with photoelectric cells (Wireless Timing Radio-Controlled, Brower Timing System, Draper, UT). Start time was determined by the subject; therefore, the 10-m performance time did not include reaction time.

RSA. The RSA test was assessed through 6 repetitions of maximal 2 × 15-m shuttle sprints (~6 s) departing every 20 s. During the 14-s recovery between sprints, subjects had a passive standing recovery. Three seconds before starting each sprint, subjects were asked to assume the ready position and await the start signal. Strong verbal encouragement was provided to each subject during all sprints. This test was adapted from previous cycling and

running tests (18,27) that have been shown to be reliable and valid to estimate RSA (27). Three scores were calculated for the RSA test: the best sprint time (RSA_{best} ; s), usually the first sprint; the mean sprint time (RSA_{mean} ; s); and the percent sprint decrement (RSA_{dec} ; %), calculated as follows (27):

total time/ideal time \times 100; where the ideal time = 6 RSA_{best} .

HR during the submaximal run. Mean HR and peak HR reached during the 6-min submaximal run (60% V_{IFT}), expressed as a percentage of HR_{max} (% HR_{6mean} and % HR_{6peak}), were recorded (4).

Postexercise HR recovery assessment. Parasympathetic function was assessed during the 10-min period after the 6-min submaximal exercise test, as described previously (7,8). At the end of exercise, all subjects immediately sat passively on a chair placed adjacent to the track. Time duration between the end of exercise and sitting was less than 5 s. Particular attention to this detail was made because differences in body posture have been shown to result in different absolute HR recovery values. HR recovery was calculated by 1) taking the absolute difference between the final HR at exercise completion and the HR recorded after 60 s of recovery (HRR_{60s}), 2) taking the time constant of the HR decay obtained by fitting the 10-min postexercise HR recovery into a first-order exponential decay curve ($HRR\tau$), or by 3) analyzing the first 30 s (from the 10th to the 40th seconds) of HRR via semilogarithmic regression analysis (T30) (7,8).

Time-varying vagal-related HRV index. Whereas a progressive increase in the R–R interval is generally observed during the initial 5 min of HRR , on shorter scales (i.e., 15–60 s), the curve is piecewise linear with superimposed oscillations. Thus, a time-varying vagal-related index, the root mean square of successive differences in the R–R intervals (RMSSD), was calculated for each of the subsequent 30-s segments of recovery ($RMSSD_{30s}$). To smooth any transient outliers in the HRV plots (HRV vs recovery time), a median filter operation was applied where each value was replaced with the median of the value as well as the preceding and following values. The first and last values were not median filtered (7,8).

Short-term resting HRV analysis. HRV analyses were performed on the last 5 min of the 10-min recovery period in the seated position. The mean HR ($HR_{5-10min}$), the standard deviation of normal R–R intervals ($SDNN_{5-10min}$), and the root-mean-squared difference of successive normal R–R intervals ($RMSSD_{5-10min}$) were calculated for the 5-min period. Power frequency analysis was performed sequentially with a fast Fourier transform based on a nonparametric algorithm with a Welch window after the ectopic-free data were detrended and resampled. A fixed linear resampling frequency of 1024 equally spaced points per 5-min period was used. The power densities in the LF band (0.04–0.15 Hz) and the HF band ($>$ 0.15–0.50 Hz) were calculated from each 5-min spectrum by integrating

the spectral power density in the respective frequency bands. The $SDNN_{5-10min}$, $RMSSD_{5-10min}$, $LnHF_{5-10min}$ (natural log of HF power density), the normalized HF power ($HFnu_{5-10min}$, calculated as the $HF/(LF+HF)$ ratios), and the $HR_{5-10min}$ were retained for statistical analysis (28).

Statistical analyses. The distribution of each variable was examined with the Kolmogorov–Smirnov and Shapiro–Wilk normality tests. When data were skewed (i.e., HF power density), data were transformed by taking the natural logarithm to allow parametric statistical comparisons that assume a normal distribution. Reliability of HR measurements during submaximal exercise and HRV indices during recovery were assessed via 1) a paired Student's *t*-test, 2) the interclass correlation coefficient, 3) the square root of the error-mean-square, standard error of measurements (SEM) (30), and 4) the minimum difference to be considered real (MD), which represents the limit under which the observed difference is within that of what might be expected to be observed in repeated testing due to the noise of the measurement (30). Physical performance and parasympathetic function indices were analyzed using a two-factor repeated-measures ANOVA, with one between factor (training type; RS vs HIT) and one within factor (period; pretraining vs posttraining). Changes through the training period were analyzed in each group using a one-factor ANOVA (period; pretraining vs posttraining). For time-varying $RMSSD_{30s}$, a three-factor repeated-measures ANOVA with one between factor (training type; RS vs HIT) and two within factors, period (pretraining vs posttraining) and time (19 repeated measures during the recovery), was used to examine the main effects and/or interactions of training type, period, and time during recovery. For each ANOVA, if a significant interaction was identified, a Tukey's *post hoc* test was used to further delineate differences between training type, period, and time. For all analyses, the level of significance was set at $P < 0.05$. If no significant effects were observed, but a tendency towards significance ($P < 0.1$) was apparent, then effect sizes (ES) were calculated. When calculating effect sizes, the pretraining standard deviations for the RS and HIT groups were applied. If there was at least a medium effect size ($>$ 0.50) but the statistical power was low, the likelihood of a type II error was noted. Linear regressions with Pearson's coefficients were used to establish the respective relationships between (improvement in) physical performance and parasympathetic indices. Others polynomial regressions were rejected on the basis of importantly higher residuals. All statistical analyses were carried out using Minitab 14.1 software (Minitab Inc, Paris, France), and data herein are presented as means and standard deviations (\pm SD).

RESULTS

Subjects. Two of the seventeen subjects initially involved in the experiment were excluded because of their irregular participation in the training program. The

remaining 15 subjects (RS, $N = 8$; HIT, $N = 7$) participated in $92 \pm 2.1\%$ of the training sessions. There was no difference in the mean age, Tanner stage, weight, or height between groups (16.0 ± 0.8 yr, $IV = 3$ and $V = 5$, 74.0 ± 6.1 kg and 179.1 ± 8.6 cm for RS and 15.5 ± 0.7 yr, $IV = 3$ and $V = 4$, 77.1 ± 6.1 kg and 177.9 ± 10.0 cm for HIT group). Posttraining physical performance and parasympathetic indices were also similar between groups (all P at least > 0.14 , Tables 2 and 3).

HR responses to the training sessions. Mean HR during the first session in RS was 162.7 ± 7.3 bpm or $82.8 \pm 3.2\%$ HR_{max}, which was lower ($P < 0.05$) than the corresponding values in HIT (180.4 ± 4.6 bpm or $91.4 \pm 3.1\%$ HR_{max}). Peak HR reached in RS was 193.1 ± 6.4 or $97.5 \pm 2.7\%$ HR_{max}, which was similar ($P = 0.62$) to HIT (192.0 ± 9.1 or $96.2 \pm 4.8\%$ HR_{max}). Mean HR during the last session in RS was 160.1 ± 9.5 bpm or $81.0 \pm 4.8\%$ HR_{max}, which was lower ($P < 0.05$) than the corresponding values in HIT (182.1 ± 4.1 bpm or $92.7 \pm 3.8\%$ HR_{max}). Peak HR reached in RS was 192.3 ± 6.9 or $97.1 \pm 3.3\%$ HR_{max}, which was similar ($P = 0.54$) to HIT (193.1 ± 8.2 or $96.6 \pm 5.2\%$ HR_{max}).

Reproducibility of HR measures during and after the submaximal exercise. Mean values of % HR_{6mean} and % HR_{6peak} at W-1 and W0 were similar ($P = 0.29$ and $P = 0.32$). ICC, SEM, and MD values were 0.77, 0.7 bpm, and 1.9 bpm for % HR_{6mean}, and 0.73, 1.9 bpm, and 5.3 bpm for % HR_{6peak}. For parasympathetic function, all calculated HR-derived indices indicated good reliability. For HRR_{60s}, calculated values were t -test $P = 0.56$, ICC = 0.70, SEM = 10.1 s, and MD = 27.9 bpm; for HRR₇, t -test $P = 0.84$, ICC = 0.86, SEM = 7.0 s, and MD = 19.2 s; for T30, t -test $P = 0.66$, ICC = 0.73, SEM = 12.2 s, and MD = 33.8 s; for SDNN_{5-10min}, t -test $P = 0.53$, ICC = 0.69, SEM = 15.1 ms, and MD = 41.8 ms; for RMSSD_{5-10min}, t -test $P = 0.59$, ICC = 0.71, SEM = 14.2 ms, and MD = 39.3 ms; for LnHF_{5-10min}, t -test $P = 0.50$, ICC = 0.69, SEM = 0.36 ms²/Hz, and MD = 0.9 ms²/Hz; for

TABLE 3. Parasympathetic indices calculated before (pre) and after (post) the training period in the repeated-sprint (RS) and high-intensity intermittent training (HIT) groups.

	RS		HIT	
	Pre	Post	Pre	Post
HRR _{60s} (bpm)	64.4 ± 15.5	70.1 ± 19.5	60.0 ± 12.2	75.6 ± 13.6
T30 (s)	96.4 ± 29.5	90.9 ± 21.9	108.8 ± 28.3	77.2 ± 46.6
HRR ₇ (s)	48.3 ± 16.8	42.1 ± 17.1	51.9 ± 17.1	23.9 ± 17.1**
SDNN _{5-10min} (ms)	48.3 ± 23.1	54.6 ± 24.5	54.9 ± 18.2	64.1 ± 11.1
RMSSD _{5-10 min} (ms)	23.8 ± 14.2	36.1 ± 18.8	20.6 ± 12.2	38.8 ± 16.8*
LnHF _{5-10min} (ms ² /Hz)	5.0 ± 1.3	5.7 ± 1.2	5.0 ± 1.0	6.1 ± 0.7
HFnu _{5-10min}	0.23 ± 0.1	0.29 ± 0.1	0.21 ± 0.1	0.28 ± 0.1
HR _{5-10min} (bpm)	84.2 ± 4.8	79.6 ± 7.2	87.5 ± 10.8	80.3 ± 9.3

Mean (± SD) values for absolute difference between the final HR at exercise completion and the HR recorded after 60 s of recovery (HRR_{60s}), time constant of the HR decay (HRR₇), short-term HR time constant (T30), standard deviation of normal R-R intervals (SDNN_{5-10min}), root-mean-square difference of successive normal R-R intervals (RMSSD_{5-10min}), natural log of high-frequency power density (LnHF_{5-10min}), normalized HF power (HFnu), and mean HR (HR_{5-10min}) calculated for the 5-min period. * Significant difference between pre and post ($P < 0.05$); ** significant difference between pre and post ($P < 0.001$).

HFnu_{5-10min}, t -test $P = 0.61$, ICC = 0.69, SEM = 0.06, and MD = 0.02; for HR_{5-10min}, t -test $P = 0.75$, ICC = 0.88, SEM = 3.9 bpm, and MD = 10.8 bpm.

Effect of RS and HIT training on physical performance. Table 2 shows mean physical performance values for each group before and after the training period. The relative changes in physical performance for RS and HIT groups are also illustrated in Figure 1. Pooling the two groups together, there was a significant period effect for V_{IFT} ($P = 0.003$), CMJ ($P = 0.02$), 4×5 m ($P = 0.03$), RSA_{mean} ($P = 0.05$), and RSA_{best} ($P = 0.05$), but not for 10 m ($P = 0.17$) or RSA_{dec} ($P = 0.20$). In the RS group only, CMJ was improved ($P = 0.04$), whereas in HIT, improvement was significant for V_{IFT} ($P = 0.03$), CMJ ($P = 0.04$), RSA_{best} ($P = 0.02$), and RSA_{mean} ($P = 0.05$).

Effect of RS versus HIT training on HR during submaximal exercise. As presented in Table 2, % HR_{6mean} tended to decrease after training from 80.5 ± 2.1 to $78.1 \pm 3.4\%$ HR_{max} ($P = 0.09$, ES = 0.28) for the RS group and from 80.6 ± 3.8 to $77.5 \pm 2.0\%$ HR_{max} ($P = 0.07$, ES = 0.31) for the HIT group. % HR_{6peak} decreased significantly from 88.4 ± 2.2 to $85.8 \pm 3.2\%$ HR_{max} ($P = 0.02$) in RS, and from 88.7 ± 2.7 to $83.8 \pm 1.7\%$ HR_{max} ($P < 0.001$) in HIT.

Effect of RS versus HIT training on parasympathetic function. Figure 2 shows, for both groups, the average time course of RMSSD_{30s} after the 6-min submaximal exercise, both before and after the training period. When considering all data together, there were significant period (pretraining vs posttraining) ($P < 0.001$) and time ($P < 0.01$) effects on RMSSD_{30s}. There was no time × training type interaction ($P = 0.99$), whereas training type × period was significant ($P = 0.03$). When considering each group separately, no significant time effect was observed for RMSSD_{30s} before the training period ($P = 0.35$ and

TABLE 2. Physical performance parameters measured before (pre) and after (post) the 9-wk training period in the repeated-sprint (RS) and high-intensity intermittent training (HIT) groups.

	RS		HIT	
	Pre	Post	Pre	Post
10 m (s)	1.88 ± 0.1	1.86 ± 0.1	1.89 ± 0.1	1.87 ± 0.1
CMJ (cm)	47.1 ± 4.4	49.3 ± 2.6*	45.9 ± 4.1	48.7 ± 3.1*
4 × 5 m (s)	5.44 ± 0.4	5.26 ± 0.1	5.50 ± 0.3	5.33 ± 0.5
RSA _{best} (s)	5.72 ± 0.1	5.70 ± 0.2	5.79 ± 0.1	5.71 ± 0.1*
RSA _{mean} (s)	5.93 ± 0.2	5.87 ± 1.7	5.99 ± 0.1	5.90 ± 0.2*
RSA _{dec} (%)	3.7 ± 2.2	3.0 ± 0.8	3.4 ± 1.5	1.9 ± 1.1
V_{IFT} (km·h ⁻¹)	20.0 ± 1.0	21.1 ± 1.4	19.2 ± 1.9	21.3 ± 2.1*
% HR _{6mean}	80.5 ± 2.1	78.1 ± 3.4	80.6 ± 3.8	77.5 ± 1.9
% HR _{6peak}	88.8 ± 2.2	85.8 ± 3.2*	88.7 ± 2.7	83.8 ± 1.6*

Mean (± SD) values for 10-m sprint time (10 m), 4×5 -m shuttle run (4×5 m), countermovement jump (CMJ), best time during the RS ability test (RSA_{best}), mean of the sprint during the RSA test (RSA_{mean}), RSA speed decrement (RSA_{dec}), velocity reached at the end of the 30-15_{IFT} test (V_{IFT}), and mean (% HR_{6mean}) and peak HR (% HR_{6peak}) during the 6-min submaximal exercise test. * Significant difference between pre and post ($P < 0.05$).

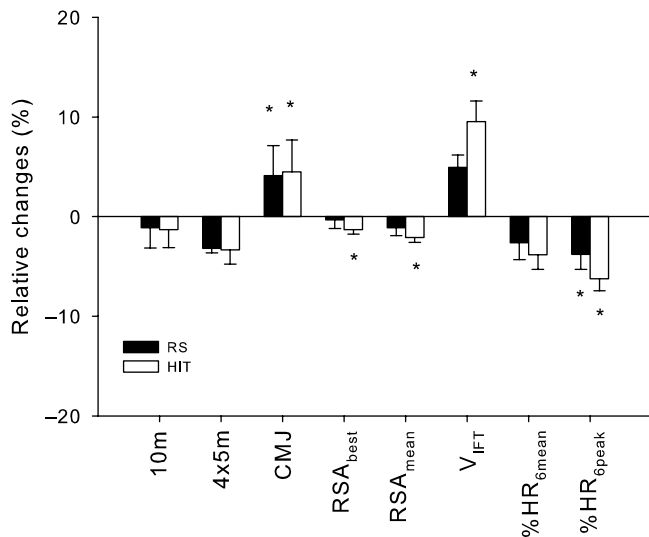


FIGURE 1—Training-induced change in physical performance and cardiac cost of submaximal exercise, 10-m sprint time (10 m), 4 × 5-m shuttle run (4 × 5 m), countermovement jump (CMJ), best time during the repeated-sprint ability test (RSA_{best}), mean sprint time during the RSA test (RSA_{mean}), velocity reached at the end of the 30–15_{IFT} (V_{IFT}), and mean (%HR_{6mean}) and peak HR (%HR_{6peak}) during the 6-min submaximal exercise. RSA decrement (RSA_{dec}) has been excluded for figure clarity (−26.1 ± 28.8 vs −66.7 ± 58.0% for RS vs HIT, respectively). *Significant difference between pre- and posttraining ($P < 0.05$).

0.29 for RS and HIT, respectively), whereas there was a significant time effect after training for the HIT group ($P = 0.04$) but not for the RS group ($P = 0.09$). Mean changes in parasympathetic indices after RS and HIT training are presented in Table 3, and the relative changes

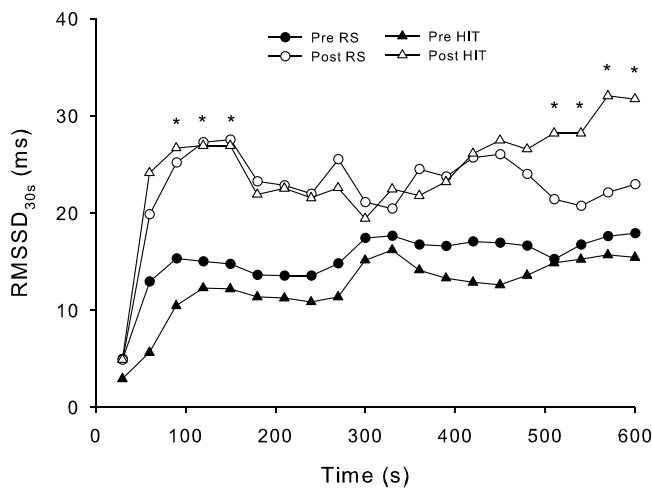


FIGURE 2—Average root mean square of successive differences in the R–R intervals measured on successive 30-s segments (RMSSD_{30s}) during the 10-min recovery period after the 6-min submaximal exercise bout (60%V_{IFT}), as calculated for participants of repeated-sprint (RS) and high-intensity intermittent training (HIT) groups, before (pre) and after (post) the training period. *Significant within-group time effect; that is, the difference vs RMSSD_{30s} at 30 s after the end of exercise during the same test session ($P < 0.05$). For figure clarity, error bars have been removed.

are illustrated in Figure 3. Taking both groups together, there was a significant period effect for HR₆₀ ($P = 0.05$), T30 ($P = 0.05$), HRR τ ($P < 0.001$), RMSSD_{5–10min} ($P = 0.002$), LnHF_{5–10min} ($P = 0.01$), HFnu_{5–10min} ($P = 0.002$), and HR_{5–10min} ($P = 0.01$). However, there was no period effect for SDNN_{5–10min} ($P = 0.19$). RS training resulted in no significant changes to parasympathetic function, whereas HIT induced significant improvements in RMSSD_{5–10min} ($P = 0.05$) and HRR τ ($P < 0.001$) and also tended to increase LnHF_{5–10min} ($P = 0.09$, ES = 0.48). Differences between pre- and posttraining HRR τ values for the HIT group were greater than the calculated MD, indicating that the effects of training overcame the magnitude of eventual measurement error. The absolute decrease in T30 (-32.2 ± 36.5 vs -5.5 ± 23.8 s for HIT vs RS, respectively; $P = 0.04$) and in HRR τ (-30.2 ± 9.6 vs -5.2 ± 8.3 s for HIT vs RS, respectively; $P < 0.001$) attributable to the training program were higher in HIT compared with RS. The HIT group showed a nonsignificant trend toward a higher increase in RMSSD_{5–10min} compared with the RS group ($P = 0.09$), with a moderate effect size between groups (ES = 0.38).

Relationships between physical performance and parasympathetic function indices. When pooling all subjects together, there was a positive relationship between the decrease in HRR τ and the decrease in mean RSA time ($r = 0.62$, $P = 0.02$, Fig. 4). There was also a significant negative correlation between the increase in

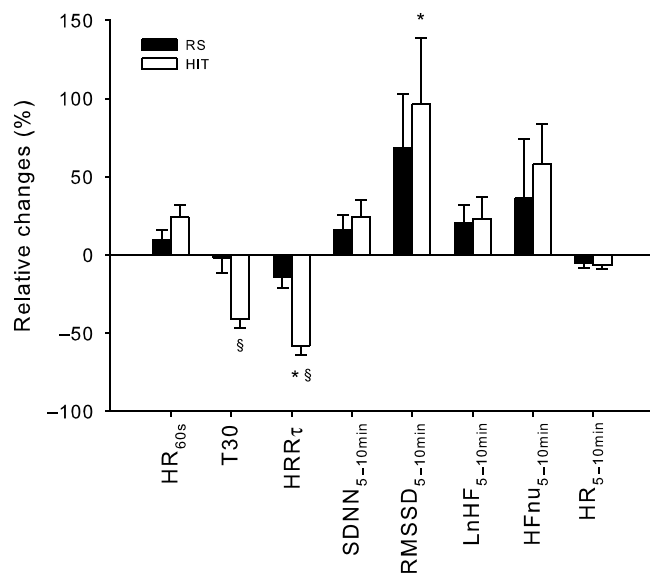


FIGURE 3—Training-induced change in parasympathetic indices, absolute difference between the final HR at exercise completion and the HR recorded after 60 s of recovery (HRR_{60s}), time constant of the HR decay (HRR τ), short-term HR time constant (T30), standard deviation of normal R–R intervals (SDNN_{5–10min}), root-mean-square difference of successive normal R–R intervals (RMSSD_{5–10min}), natural log of high-frequency power density (LnHF_{5–10min}), normalized HF power (HFnu_{5–10min}), and mean HR (HR_{5–10min}) calculated for the 5-min period. *Significant difference between pre and post measurements ($P < 0.05$); § significant difference between RS and HIT training ($P < 0.05$).

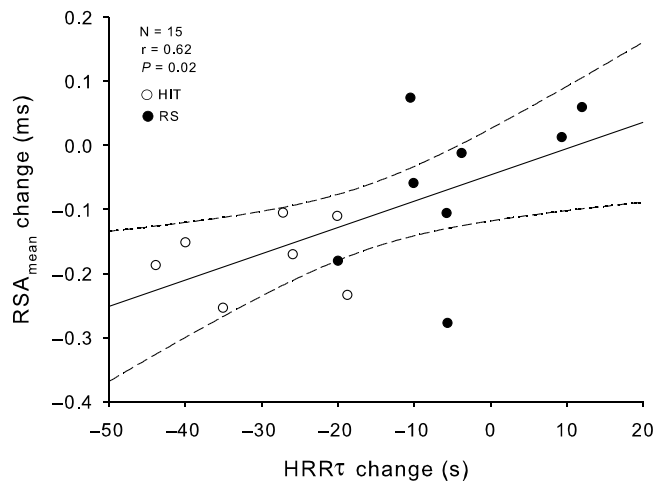


FIGURE 4—Relationship between changes in HR recovery ($HRR\tau$) and changes in mean repeated-sprint ability (RSA_{mean}) after the training period in the repeated-sprint (RS) and high-intensity intermittent training (HIT) groups. Shaded lines represent 95% confidence intervals.

$RMSSD_{5-10min}$ and the decrease in mean RSA time ($r = -0.55$, $P = 0.05$). These relationships were no more significant at the group level ($P = 0.22$ and 0.71 for RS and HIT, respectively). There was no relationship shown between the change in parasympathetic function indices and changes in physical performance, or between posttraining parasympathetic function indices and absolute or change in physical performances. During pretraining tests (W0), CMJ was strongly related to RSA_{best} , RSA_{mean} , and V_{IFT} ($r = 0.85$ and $P < 0.001$, $r = 0.62$ and $P = 0.01$, and $r = 0.69$ and $P < 0.01$). RSA_{mean} and RSA_{best} were also related to V_{IFT} ($r = 0.84$ and $P < 0.001$, and $r = 0.63$ and $P = 0.01$). During the posttraining tests (W10), similar relationships were observed.

DISCUSSION

The present study is the first to investigate the longitudinal effects of two different supramaximal training regimens on physical performance and parasympathetic function in already trained adolescents. Results highlight that repeated HIT running had a more pronounced effect on overall physical fitness and autonomic function compared with all-out RS training. This was evidenced by the significantly greater improvement in intermittent aerobic performance, RSA, and postexercise parasympathetic reactivation indices. Moreover, the decrease in the postexercise HR recovery time constant and the increase in HRV vagal-related indices were related to the improvement in RSA, suggesting that these variables may be useful measurement tools for coaches and clinicians to monitor the effectiveness of their training programs.

Effects of RS versus HIT running on physical fitness. Whereas the positive effects of intense aerobic training on physical fitness and health-related indices have already been investigated in young individuals (2,26), our

study is the first to describe the impact of two different supramaximal regimens on adolescent physical performance. The disparate improvements in physical fitness indices shown after the different training regimens illustrate that adaptations occurring with training seem specific to training type (or training intensity). Indeed, only a significant increase in CMJ was observed in the RS group, whereas CMJ, V_{IFT} , RSA_{best} , and RSA_{mean} were all enhanced in the HIT group (Table 2 and Fig. 1). These distinct effects are consistent with what has been observed after similar high-intensity training interventions in adults. For example, Mohr et al. (24) show in their 8-wk study that HIT versus RS training was more effective at improving running distance during the yo-yo test (comparable with the 30–15_{IFT} used herein), time to exhaustion during a progressive incremental running test, and RS fatigue. Because training sessions in our study were matched for exercise duration and frequency (Table 1), the greater aerobic energy system requirements of the HIT program likely contribute to the differences observed between programs. Mean HR was significantly higher during HIT than during RS (82.8 ± 3.2 vs $91.4 \pm 3.1\%$ HR_{max} for RS and HIT, respectively) for a similar total exercise duration. This is consistent with the 85.2 ± 0.7 vs $97.3 \pm 0.4\%$ of aerobic participation recently estimated for similar RS and HIT trials, respectively (7). Thus, whereas the RS training program was highly specific to the RSA test, and could be considered “maximal” from a mechanical and muscular recruitment point of view, the oxygen and metabolic demands of this training may have been too low to stimulate aerobic metabolic adaptations. Because the aptitude to recover during short, intense exercise bouts is closely related to muscular oxidative capacities (18), the lack of improvement in aerobic-related tests (i.e., 30–15_{IFT}) could explain why the RS program was ineffective at improving RSA_{mean} (24). Nevertheless, the decreases in % HR_{6mean} and % HR_{6max} during submaximal exercise were similar for both groups (Table 2), suggesting that both training regimens enhanced submaximal aerobic function.

Effects of RS versus HIT running on postexercise parasympathetic function. An important finding from the present study was that the addition of HIT training to the normal training program of trained adolescents induced an increase in parasympathetic reactivation after a submaximal exercise bout, as observed by the significantly shorter $HRR\tau$ (-58.1 vs -13.8% for HIT vs RS, respectively, $P < 0.001$) and higher $RMSSD_{5-10min}$ (96.2 vs 68.6% for HIT vs RS, respectively, $P = 0.10$, $ES = 38$) (Fig. 3). Before training, as illustrated in Figure 2, the lack of a significant increase in $RMSSD_{30s}$ during the 10-min recovery period in both groups indicated poor levels of parasympathetic reactivation after the 6-min submaximal exercise period. After HIT training, however, a gradual elevation of $RMSSD_{30s}$ was observed during the 10-min recovery period, whereas similar pretraining levels were still observed after RS training. Because it is well

established that reduced cardiac vagal tone after exercise is related to increased cardiovascular risk, our data encourage the prescription of HIT rather than RS training to improve health-related indices of cardiovascular disease risk (3,28). The fact that HRR indices seemed to be more sensitive training markers than those obtained via HRV ($P < 0.001$ for $HRR\tau$ vs $P = 0.05$ for $RMSSD_{5-10min}$ in the HIT group) may be attributable to differences in their physiological determinants (6,8). Previous investigations have suggested that HRR and HRV indices might illustrate distinct but complementary aspects of parasympathetic function; HRR may be more related to the vagal “tone”, whereas HRV may be a better indicator of the parasympathetic “modulation” (8). Another explanation may come from the lower statistical power in HRV indices. Indeed, because of the larger SD, at least 10–12 subjects per group would have been needed to reach a similar level of statistical power (0.80) for HRV analysis compared with HRR_{60s} .

The present study is the first to examine the effect of differing levels of supramaximal training on postexercise autonomic function. Previous longitudinal studies in young, trained athletes have reported either small improvements (16,25) or no change in parasympathetic function (19) after 5 wk (16) to 5 months (19,25) of intense training. Because participation in high-intensity activities seems to be the critical component of a training program for improvement of autonomic function (9,10,21), the lack of an increase in parasympathetic regulation in these studies might be related to insufficient training intensities. Nevertheless, because these three field studies were conducted on athletes during their competitive season (16,19,25), very few training details were provided, and it is thus difficult to compare the exercise intensities used. However, there is no evidence to suggest that any supramaximal intensity was applied. Regarding the present study, we expected both supramaximal regimens in the present study to be effective at enhancing postexercise parasympathetic reactivation, but this was not the case (Table 3).

Comparison of RS or HIT training on parasympathetic function has not been previously evaluated in either young individuals or adults. Because we recently observed parasympathetic reactivation to be impaired after similar exercise stimuli in adults (7), we expected these two training regimens to induce similar long-term changes to parasympathetic function in adolescents. However, the improvement in postexercise vagal activity was only observable after HIT, and not after RS training (Fig. 3). Therefore, the perturbation of the parasympathetic reactivation *per se* does not necessarily constitute the stimulus to modify autonomic function. As for the aerobic performance, the aerobically “submaximal” nature of the RS training (7) might explain the lack of an improvement in parasympathetic function. The fact that neither V_{IFT} nor parasympathetic function improved during the RS training period is consistent with previous findings showing that the increase in vagal activity is often related to changes in

cardiorespiratory function (1). Another explanation for the negligible influence that the RS training had on parasympathetic reactivation could be a recurrent inhibition of a postexercise parasympathetic effect by a high sympathetic activity and an associated persistence in metabolites during that period. Indeed, there are complex interactions that occur between the sympathetic and vagal systems with respect to HR regulation, resulting in reduced or amplified vagal stimulation (22). Although we did not measure blood lactate or plasma epinephrine concentration in the present study, one could speculate that the sympathetic activity and stress system metabolites were more important after RS training (7,24) when compared with HIT training. Finally, $HRR\tau$ is also influenced by the clearance of metabolites (i.e., plasma epinephrine, H^+ , or ion lactate) (8) in addition to vagal tone. This remarkable shortening of $HRR\tau$ after HIT training might rely on the specific amelioration of muscular oxidative capacity and the effectiveness of transmembrane ion efflux (i.e., higher lactate- H^+ transport capacity, increased amount of both monocarboxylate transporters (MCT), and Na^+/H^+ -exchanger isoform 1 or higher activity of Na^+/K^+ pumps), as previously described (24).

Relationship between parasympathetic function and physical fitness. When all subjects were pooled, the decrease in the postexercise HR recovery time constant and the increase in beat-to-beat HR variability ($RMSSD_{5-10min}$) were related to the improvement in RSA (Fig. 4). Concomitant changes in cardiorespiratory fitness (i.e., maximal oxygen uptake) and vagal-related HRV indexes have already been reported (1,25). Nevertheless, the present study is the first to observe a link between postexercise parasympathetic function and RSA. $HRR\tau$ (but not HR_{60s} or T30, which are linked to the direct parasympathetic effect on HR), reflecting both central parasympathetic tone and the peripheral ability to eliminate muscles stress metabolites (8), can be seen as a global index of cardiovascular adjustment immediately after exercise. RSA has been linked to muscular PCr and glycogen stores, muscle buffer capacity, local oxygen availability (18), and the kinetics of oxygen consumption at the onset of submaximal exercise (12). Similarly, one may speculate that shorter off-HR kinetics indirectly reflect a decrease in O_2 off-kinetics and, consequently, a faster restoration of myoglobin stores and, consequently, PCr. However, questions regarding whether on- or off- O_2 kinetics, $HRR\tau$, and HRV kinetics are linked, and whether they rely on similar regulation mechanisms or are modified to the same extent by any supramaximal training regimen, remain unanswered. Nevertheless, considering the ease of obtaining postexercise HR measurements, future research should examine whether the kinetics of HRV recovery recordings might assist with the assessment of training program effectiveness, both for cardiac rehabilitation patients and after strength and conditioning programs in athletes.

The present study is not without its limitations. From the health perspective, evaluation of the long-term influence of supramaximal exercise on autonomic function may be of

more interest for sedentary individuals and patients compared with trained athletes. However, our decision to use team-sport players as subjects was based on the assumption that these individuals would cope more easily with the supramaximal intermittent regimen, which would likely have been exhausting (and potentially dangerous) to sedentary subjects. However, because trained subjects often display fast HR recovery kinetics (6), the present findings should be extended to sedentary subjects with caution. Whether individuals with low habitual activity levels would display similar responses as those observed in the present study requires confirmation. Another potential flaw to the current study was that our experimental design precluded full determination of whether the training programs (particularly the HIT), independent of the handball training program, were responsible for the outcomes reported. This issue could be addressed in the future by applying the same study design to a control group (handball training only) and to sedentary subjects.

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In conclusion, the addition of HIT to the usual exercise training program of adolescents had a significantly more pronounced effect on postexercise parasympathetic reactivation, RSA, and maximal intermittent aerobic performance compared with the addition of repeated all-out sprint training. HIT, therefore, seems more appropriate than an RS regimen for the lowering of cardiovascular disease risk-related indices in adolescents, which could be beneficial for lowering risk in later adulthood. Moreover, the shortening of the postexercise HR recovery time constant and the increase in beat-to-beat HRV were related to the improvement of RSA. The latter finding suggests that analysis of HR and HRV kinetics during the postexercise recovery phase might be a useful tool for coaches and clinicians to monitor during various training interventions.

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