Overspeed HIIT in Lower-Body Positive Pressure Treadmill Improves Running Performance

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ABSTRACT

GOJANOVIC, B., R. SHULTZ, F. FEIHL, and G. MATHESON. Overspeed HIIT in Lower-Body Positive Pressure Treadmill Improves Running Performance. *Med. Sci. Sports Exerc.*, Vol. 47, No. 12, pp. 2571–2578, 2015. **Purpose**: Optimal high-intensity interval training (HIIT) regimens for running performance are unknown, although most protocols result in some benefit to key performance factors (running economy (RE), anaerobic threshold (AT), or maximal oxygen uptake ($\dot{V}O_{2max}$)). Lower-body positive pressure (LBPP) treadmills offer the unique possibility to partially unload runners and reach supramaximal speeds. We studied the use of LBPP to test an overspeed HIIT protocol in trained runners. **Methods**: Eleven trained runners (35 ± 8 yr, $\dot{V}O_{2max}$, 55.7 ± 6.4 mL·kg^{-1}·min^{-1}) were randomized to an LBPP (n = 6) or a regular treadmill (CON, n = 5), eight sessions over 4 wk of HIIT program. Four to five intervals were run at 100% of velocity at $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$) during 60% of time to exhaustion at v$\dot{V}O_{2max}$ (T_{lim}) with a 1:1 work:recovery ratio. Performance outcomes were 2-mile track time trial, $\dot{V}O_{2max}$, v$\dot{V}O_{2max}$, vAT, T_{lim}, and RE. LBPP sessions were carried out at 90% body weight. **Results**: Group–time effects were present for v$\dot{V}O_{2max}$ (CON, 17.5 vs. 18.3, P = 0.03; LBPP, 19.7 vs. 22.3 km·h^{-1}; P < 0.001) and T_{lim} (CON, 307.0 vs. 404.4 s, P = 0.28; LBPP, 444.5 vs. 855.5, P < 0.001). Simple main effects for time were present for field performance (CON, −18; LBPP, −25 s; P = 0.002), $\dot{V}O_{2max}$ (CON, 57.6 vs. 59.6; LBPP, 54.1 vs. 55.1 mL·kg^{-1}·min^{-1}; P = 0.04) and submaximal HR (157.7 vs. 154.3 and 151.4 vs. 148.5 bpm; P = 0.002). RE was unchanged. **Conclusions**: A 4-wk HIIT protocol at 100% v$\dot{V}O_{2max}$ improves field performance, v$\dot{V}O_{2max}$, $\dot{V}O_{2max}$ and submaximal HR in trained runners. Improvements are similar if intervals are run on a regular treadmill or at higher speeds on a LPBB treadmill with 10% body weight reduction. LBPP could provide an alternative for taxing HIIT sessions. **Key Words:** ANTIGRAVITY, INTERVAL TRAINING, $\dot{V}O_{2max}$, HIIT, OVERSPEED, LBPP

Performance in distance running can be enhanced by multiple training techniques, aiming to develop the key determinants of running ability. Maximal oxygen uptake ($\dot{V}O_{2max}$) has been considered as one of the main determinants of performance in middle- to long-distance running, and multiple studies have shown correlation between $\dot{V}O_{2max}$ and performance (7). Other factors have also been identified, such as endurance, running economy (RE) (9,38), velocity at lactate or anaerobic thresholds (vAT), and velocity at $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$) (29,31). All of these parameters play a role in determining performance to various degrees depending on the distance the runner tries to master. Although a lot is known about the physiological determinants of running performance, less is known about the optimal training regimen that will help attain these objectives and how new training techniques and devices could be used efficiently.

High-intensity interval training (HIIT) has been extensively studied and accepted by coaches and sports scientists as beneficial to running performance (15,16,18). It allows an athlete to spend more time at or near $\dot{V}O_{2max}$ compared with continuous high-intensity running, provided training speeds close to v$\dot{V}O_{2max}$ are used (6). This has been shown to be optimal not only for short bouts at 100% of v$\dot{V}O_{2max}$ (15–30 s) (5,6) but also for longer intervals, which have the advantage of stimulating other physiological performance determinants (AnT and RE)(27). Using this velocity at intervals of 50% the time to exhaustion at v$\dot{V}O_{2max}$ (T_{lim}), Billat et al. showed that runners could spend 2.5 times longer at $\dot{V}O_{2max}$ compared with a continuous run at v$\dot{V}O_{2max}$. Furthermore, Billat et al. (4) and Smith et al. (37) have shown that as few as one interval (50%–75% T_{lim}) session per week for 4 wk can improve v$\dot{V}O_{2max}$ in trained runners.

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The observed adaptations also include the development of neuromuscular capabilities necessary for high-speed running and improvement of economy (32).

One particular training concept has been sparsely studied, although frequently mentioned: overspeed running (28). Few studies have tackled the issue, and most of the existing literature addresses performance and kinematics in short-distance sprinters or explosive sports. It seems interesting to consider the potential for such a training technique in endurance runners, as an important part of their training involves high-speed intervals, with running technique and economy representing key attributes for performance. The challenge to use overspeed in endurance runners could be approached with the use of new technology, such as the antigravity treadmill by Alter-G™. It is a new rehabilitation and training tool for weight-supported ambulation, which uses a lower-body positive pressure (LBPP) closed environment to partially "unweigh" the runner by 1% decrements to a minimum of 20% body weight (BW). The runner is attached at waist level and is free to move in all directions as the system provides limited horizontal stabilization. In a previous study (14), we described the use of this device and were able to show that trained runners could reach equivalent maximal metabolic intensities at 85%, 90%, and 95% of their BW during a classical $\dot{V}O_{2max}$ graded exercise test, the difference being the faster speeds they were able to reach at lower BW. We therefore set out to investigate whether a HIIT program at reduced BW in LBPP can elicit a training response and how it compares with a regular treadmill HIIT program of similar relative intensity, the difference between the two residing in the higher speeds (overspeed) used in an LBPP device.

METHODS

Subjects

Twelve healthy male runners voluntarily participated in the study (Table 1). Inclusion criteria targeted local competitive runners or triathletes, who had been regular runners for at least 3 yr and actively logging a minimum of 25 km·wk^{-1}. The running ability criteria comprised a recent 10-km personal best of less than 42 min before experience in interval/speed training, absence of injuries in the past 3 months, and no medical conditions that interfered with the ability to run. Subjects were experienced users of treadmills. All subjects signed an informed consent. The study was accepted by the institutional review board of Stanford University and was conducted according to the Declaration of Helsinki.

TABLE 1. Characteristics of study participants.

	LBPP		Control		P Value
	Mean	SD	Mean	SD	
Age	31.7	5.2	38.4	9.7	0.17
Height (m)	1.82	0.10	1.78	0.04	0.38
Weight (kg)	77.3	5.2	75.9	3.6	0.8
BMI (kg·m^{-2})	23.4	2.0	24.1	1.6	0.17
Average (km·wk^{-1})	31.4	25.9	42.6	14.4	0.41
Running experience (yr)	10.7	2.7	15.6	9.7	0.26
Personal best at 10 km (min:s)	40:22	03:15	39:54	03:03	0.81

BMI, body mass index.

Study Design

After collection of anthropometric characteristics, each subject underwent an outdoor running performance evaluation and was thereafter randomized to one of two groups: the control group (CON) was to continue testing and training on a regular treadmill, whereas the antigravity treadmill group (LBPP) would be using the LBPP device. The following tests were performed in the first week before training started: a 2-mile outdoor time trial on a 400-m running track, a graded exercise test (GXT) on respective (regular or antigravity) treadmills to measure $\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, and vAT, a submaximal test at 14 km·h^{-1} to measure RE (RE, both groups were tested on a regular treadmill), and a continuous maximal exercise bout at $v\dot{V}O_{2max}$ to determine the time to exhaustion at this speed (T_{lim}). All tests were performed on a separate day with at least 48 h in between, except RE and T_{lim}, which were carried out during the same visit in that order. Subjects were instructed to abstain from caffeine, alcohol, or nicotine consumption in the 12 h preceding any test and to be fully recovered from their usual training. All laboratory tests were conducted in a climate-controlled environment (21°C–23°C, 53%–57% humidity), at approximately the same time of the day (±2 h). After the 4-wk training intervention period, the exact same tests were performed in the same order during the last week of the study. Figure 1 depicts the 6-wk study design.

Outdoor time trial. Subjects reported to the track after at least 48 h of rest and warmed up according to their personal routine for at least 20 min, which included short bursts of high-intensity running and stretching for those individuals who were used to it. The time trial was individually paced and consisted of 3.2 km (2 miles) to be covered in the shortest possible time on a 400-m synthetic outdoor track, under similar weather conditions (temperature, 20°C–25°C; humidity, 50%–60%, dry track conditions). Time was measured with a manually activated stopwatch by the same investigator. Subjects were encouraged at each lap, and they were informed of their lap splits.

$\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, and vAT measurements. Subjects reported to the laboratory after at least 24 h of rest. Running was performed on a regular treadmill at 0% grade for the CON group (Woodway Pro Series; Woodway™ GmbH, Weil am Rhein, Germany) and on the LBPP treadmill at 90% BW and 0% grade for the LBPP group (Alter-G P200; Alter-G™, Fremont, CA). After 10 min of slow-to-moderate running speed warm-up, subjects were equipped with a facemask for gas exchange measurement and proceeded with a GXT protocol starting at 9.7 km·h^{-1} (6 mph) for CON, 11.3 km·h^{-1}

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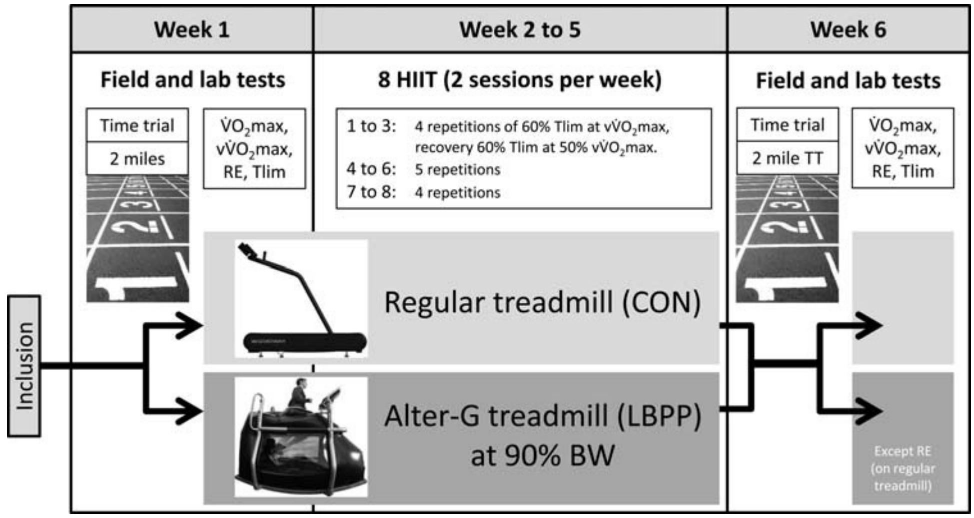

FIGURE 1—Study design. The subjects performed a 2-mile time trial on an outdoor track before randomization to one of the two treadmills. Additional laboratory testing was conducted on each treadmill before the training program started. The track test was the first posttraining outcome measure before the other laboratory tests. RE tests were all run on the regular treadmill.

(7 mph) for LBPP, and increasing by 0.8 km·h^{-1} (0.5 mph) every minute until volitional exhaustion or interruption by the investigators for safety reasons. The parameters measured were HR with a thoracic belt and wrist receiver (Polar™ RS800cx; Polar Electro Oy, Kempele, Finland), expired gas analysis, and $\dot{V}O_{2max}$, with a stationary metabolic cart (Schiller CS 200 Ergo Spirometer; Schiller Medizintechnik GmbH, Ottobrunn, Germany). The gas analysis system was calibrated before each test with ambient air and certified standardized gases. GXT was considered maximal when a plateau in $\dot{V}O_2$ was reached despite increase in work rate or when the two following criteria were satisfied: RER > 1.10, HR within 10 beats of age-predicted maximal HR (220 − age) (17). $\dot{V}O_{2max}$ was measured as the maximal average value over 10 s. $v\dot{V}O_{2max}$ was determined according to the definition of Billat et al. (3), i.e., as the minimal speed that elicits $\dot{V}O_{2max}$ (also called the "maximal aerobic speed") or if no plateau occurred in $\dot{V}O_2$, as the speed of the last completed stage. Velocity at anaerobic threshold (vAT) was determined according to the V-slope method (2).

RE, submaximal HR, and T_{lim} measurement. Subjects reported to the laboratory after at least 24 h of rest. RE was assessed in all subjects on the regular treadmill. After 6 min of running at 9.7 km·h^{-1} (6 mph), the runners were equipped with the facemask and ran for an additional minute before speed was increased to 14 km·h^{-1} (8.7 mph) for 6 min. RE was measured by averaging $\dot{V}O_2$ from the last (fifth to sixth) minute, and was expressed in milliliters of oxygen per kilogram and per kilometer (mL O_2·kg^{-1}·km^{-1}), corresponding to energetic cost of locomotion. HR was also averaged over the last minute. Once RE was assessed, the CON group stayed on the regular treadmill, whereas the LBPP group changed to the LBPP treadmill at 90% BW, and the time to exhaustion at $\dot{V}O_{2max}$ (T_{lim}) was measured. After 2 min of rest (time to change treadmills for the LBPP group), the speed was rapidly increased (over 20 s) to $v\dot{V}O_{2max}$, at which time the stopwatch was started. Subjects were verbally encouraged to keep running as long as they could until exhaustion or until the investigator stopped the treadmill for safety reasons.

HIIT program. The training program consisted of 4 wk, two HIIT sessions per week at least 48 h apart, for a total of eight training sessions. Participants reported to the laboratory and warmed up on the treadmill for 10 min at a self-selected pace interspersed with short accelerations (15–20 s) to reach interval running speed. At each HIIT session, runners completed four (sessions 1–2 and 7–8) to five (sessions 4–6) intervals at $v\dot{V}O_{2max}$ for a duration equal to 60% T_{lim}, with a 1:1 work:recovery ratio ran at 50% $v\dot{V}O_{2max}$. The LBPP runners ran all their sessions at 90% BW. Subjects were instructed to limit their remaining weekly training to a maximum of three non–high-intensity sessions (mostly endurance or subthreshold pace). Table 2 presents the training parameters and compliance with the protocol in both groups.

Statistical Analysis

Statistical analysis was carried out with repeated-measures ANOVA. The fixed factors included in the model were group

TABLE 2. Training sessions characteristics.

	LBPP		Control		
	Mean	SD	Mean	SD	*P* Value
Training speed ($v\dot{V}O_{2max}$) (km·h^{-1})	19.7	0.8	17.5	1.3	0.01*
Interval duration (60% T_{lim}) (s)	267	68	184	59	0.008**
Total planned time at $v\dot{V}O_{2max}$ (min)	152.7	40.0	109.6	34.6	0.04*
Total actual time at $v\dot{V}O_{2max}$ (min)	130.5	22.9	98.7	24.0	0.02*
Planned training time completed (%)	87.4	11.8	91.9	11.2	0.42
Sessions completed (out of eight planned)	7.8	0.4	7.8	0.5	0.9

Statistical differences (planned comparison) are indicated by asterisks.
*$P < 0.05$.
**$P < 0.01$.
$v\dot{V}O_{2max}$, minimal velocity eliciting $\dot{V}O_{2max}$.

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TABLE 3. Performance and laboratory testing parameters.

	Control					LBPP					Between groups		Interaction
	Before		After			Before		After			P Value (ANOVA)		
	Mean	SD	Mean	SD	P^a	Mean	SD	Mean	SD	P^a	Before	After	P Value
Field test													
2-mile track TT (s)	736.9	62.0	718.9	65.3	0.002*	748.4	45.8	723.3	39.7	0.002*	0.81	0.81	0.49
Average running speed at 2-mile TT ($km \cdot h^{-1}$)	15.8	1.4	16.2	1.6	0.001*	15.5	1.0	16.1	1.0	0.001*	0.76	0.76	0.51
Laboratory tests													
Absolute $\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	4.32	0.17	4.42	0.22	0.20	4.15	0.59	4.18	0.55	0.20	0.45	0.45	0.55
Relative $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	57.6	2.5	59.6	2.0	0.04**	54.1	8.3	55.1	7.6	0.04**	0.31	0.31	0.41
$v\dot{V}O_{2max}$ ($km \cdot h^{-1}$)	17.5	1.3	18.3	1.3	0.03**	19.7	0.8	22.3	1.2	<0.001***	0.01**	<0.001***	0.003*
T_{lim} (s)	307.0	85.7	404.4	113.1	0.28	444.7	103.9	855.5	317.1	<0.001***	0.26	0.003*	0.02**
vAT ($km \cdot h^{-1}$)	14.2	0.7	15.0	1.2	0.001*	16.2	0.9	17.4	1.3	0.001*	0.005*	0.005*	0.38
RE at 14 $km \cdot h^{-1}$ ($mL\ O_2 \cdot kg^{-1} \cdot min^{-1}$)	48.4	4.9	47.3	3.7	0.25	47.1	4.0	45.9	4.6	0.25	0.62	0.62	0.5
RE ($mL\ O_2 \cdot kg^{-1} \cdot km^{-1}$)	207.3	21.1	202.6	16.0	0.13	201.9	17.3	196.5	19.9	0.13	0.64	0.60	0.91
HR at 14 $km \cdot h^{-1}$ (bpm)	157.7	7.4	154.3	7.1	0.002**	151.4	12.0	148.5	11.9	0.002**	0.35	0.35	0.7

When time–group interaction was significant, before/after and between-group comparisons were made separately.

[a]With nonsignificant interaction, the P values indicated for both groups are identical because they correspond to the simple main effect of time. Same applies to the P values for between-group comparisons on the right of the table.

Statistical differences in P value within groups before and after are indicated by asterisks.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

TT, time trial.

(LBPP/CON), time (pre/post) and their interaction. The model was mixed, with participants included as a random factor nested under group. When the relevant F value was significant, the following contrasts of means were tested: pre versus post and CON versus LBPP (Fisher least significant difference). When the interaction term was not significant, the P values reported are those corresponding to the simple main effects. With a significant interaction, comparisons between levels of one factor were carried out separately at each level of the other factor. The nominal alpha was uniformly set at 0.05. The data were summarized as mean ± SD. The calculations were made with the JMP software (version 5.0; SAS Institute, Cary, NC).

RESULTS

All 12 participants completed the first week performance and physiological evaluation and entered the training program. Participants' characteristics are shown in Table 1. One subject in the CON group dropped out after the third HIIT training session because of newly occurring anterior knee pain and was hence not included in the overall analysis.

Training parameters. As expected per protocol, interval training speed ($v\dot{V}O_{2max}$) was higher in LBPP (19.7 ± 0.8 vs 17.5 ± 1.3; $P < 0.01$). Interval duration was also higher in LBPP (because of higher T_{lim} pretraining), which elicited higher total time spent at $v\dot{V}O_{2max}$ in LBPP at the end of the 4 wk of training (Table 2).

Running performance. Table 3 presents all results. There was a significant group–time interaction only for $v\dot{V}O_{2max}$ and T_{lim}; $v\dot{V}O_{2max}$ (Fig. 2) increased in both groups but more significantly in LBPP (CON, 17.5 ± 1.3 (pre) vs 18.3 ± 1.3 $km \cdot h^{-1}$ (post), $P = 0.03$; LBPP, 19.7 ± 0.8 (pre) vs 22.3 ± 1.2 (post), $P < 0.001$; interaction $P = 0.003$), whereas T_{lim} improved only in LBPP (CON, 307.0 ± 85.7 (pre) vs 404.4 ± 113.1 (post), $P = 0.28$; LBPP, 444.7 ± 103.9 (pre) vs 855.5 ± 317.1 s (post), $P < 0.001$; interaction $P = 0.02$).

Simple main effects for time were observed for 2-mile time trial performance on the track (CON, −18 s = −2.5%, 736.9 ± 62.0 (pre), 718.9 ± 65.3 s (post); LBPP, −25 s = −3.4%, 748.4 ± 45.8 (pre), 723.3 ± 39.7 s (post), $P = 0.002$), $\dot{V}O_{2max}$ (CON, 57.6 ± 2.5 (pre) vs 59.6 ± 2.0 $mL \cdot kg^{-1} \cdot min^{-1}$ (post);

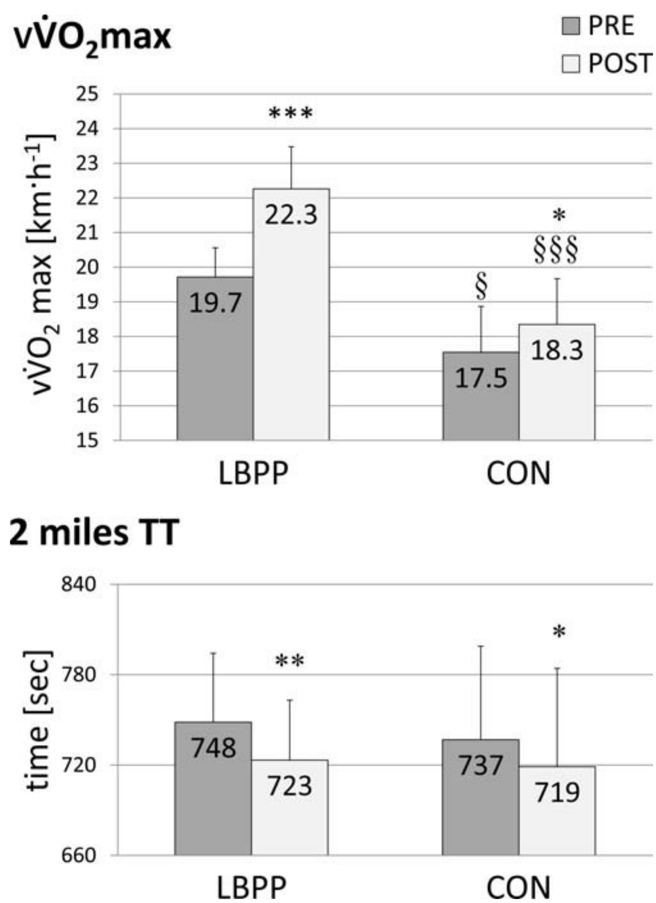

FIGURE 2—Comparison of $v\dot{V}O_{2max}$ and 2-mile time trial before/after between groups. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$ before and after within groups; §$P < 0.05$ and §§§$P < 0.001$ between CON and LBPP.

LBPP, 54.1 ± 8.3 (pre) vs 55.1 ± 7.6 (post), P = 0.04) and vAT (CON, 14.2 ± 0.7 (pre) vs 15.0 ± 1.2 km·h^{-1} (post), P < 0.05; LBPP, 16.2 ± 0.9 (pre) vs 17.4 ± 1.3 (post), P = 0.001).

RE. RE was similar between groups, and the changes observed were not statistically significant when looking at oxygen uptake at 14 km·h^{-1} (Fig. 3). However, submaximal HR at 14 km·h^{-1} improved in both groups (CON, 157.7 ± 7.4 (pre) vs 154.3 ± 7.1 bpm (post); LBPP, 151.4 ± 12.0 (pre) vs 148.5 ± 11.9 (post), P < 0.05). There was no group or group–time interaction.

DISCUSSION

In this study, we looked at the effects on running performance of a HIIT program conducted on an LBPP treadmill. This program enabled the runners to be subjected to an innovative form of overspeed running thanks to the 10% reduction in BW provided by the device. We observed similar field running performance improvements in our two groups, whether they were conducting a regular treadmill program (+2.4%) or running at overspeed on the antigravity treadmill (+3.4%). We also observed improvements in v$\dot{V}O_{2max}$, $\dot{V}O_{2max}$, vAT, and submaximal HR in both groups, whereas T_{lim} improved in LBPP only. This is the first study to our knowledge that examined the training effect of a HIIT program using overspeed in endurance athletes.

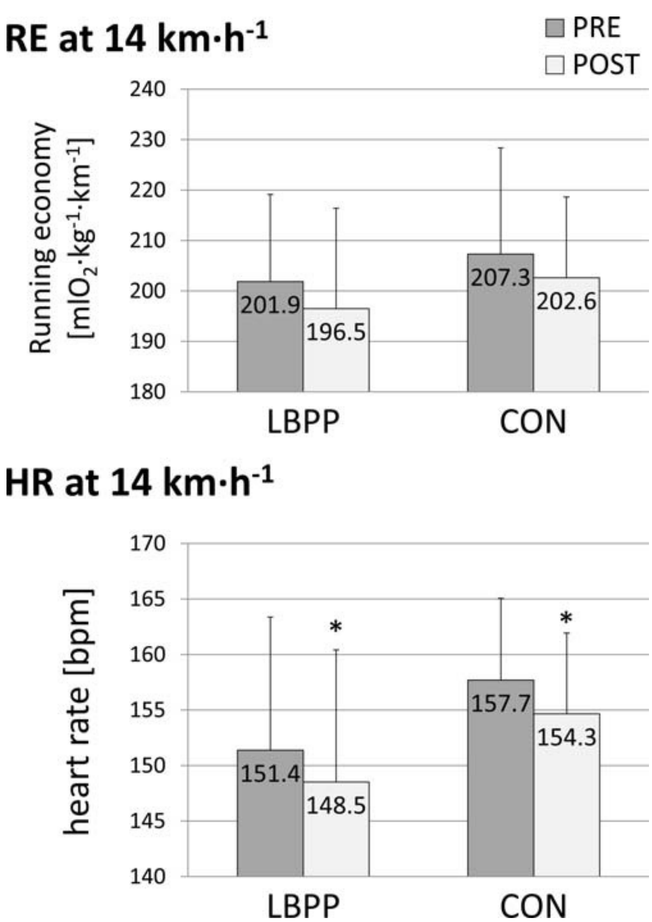

FIGURE 3—Comparison of RE and submaximal HR before/after between groups. *P < 0.05 between before and after within group; there were no differences between groups.

Track 2-mile time trial. The improvements in both groups are similar, with CON running the 2 miles 18 s faster and LBPP, 25 s faster. These are real positive effects of a HIIT training program, which have been reported in other studies: Smith et al. (37), minus 17 s on a 3000-m trial; Denadai et al. (11), minus 14 s on a 5000-m trial, both after eight 100% v$\dot{V}O_{2max}$ HIIT sessions over 4 wk; Esfarjani and Laursen (12), minus 50 s on a 3000-m trial after 10 wk of HIIT (runners were less trained in this study). High-intensity prolonged intervals have consistently shown performance effects, and our subjects matched previous findings.

v$\dot{V}O_{2max}$. Pretraining v$\dot{V}O_{2max}$ was different between groups because it was device specific and was required per protocol. Runners on the LBPP treadmill completed the tests at 90% BW, and their v$\dot{V}O_{2max}$ was 12.6% faster as expected. In a previous study, we determined v$\dot{V}O_{2max}$ at 90% BW to be 11.4% faster than on a regular treadmill, and Kline et al. (21) reported a 9.7% speed increase necessary at 90% BW to match $\dot{V}O_2$ at speeds close to v$\dot{V}O_{2max}$. Runners on the regular treadmill managed to improve from 17.5 to 18.3 km·h^{-1} (+4.6%), which matches findings from Kohn et al. (22) (peak treadmill speed improves by 5.2% after 12 similar HIIT sessions over 6 wk), Smith et al. (37) (+3.9%) and Esfarjani and Laursen (12) (+6.4% after 10 wk in less trained runners). In LBPP however, training improved v$\dot{V}O_{2max}$ from 19.7 to 22.3 km·h^{-1} (+13.2%), speeds attained while running at 90% BW. This important change in v$\dot{V}O_{2max}$ after training cannot be solely explained by LBPP training effects, or else it should have been coupled to a much larger change in field test performance in favor of the LBPP group. One potential explanation is that the runners learned how to benefit maximally from the 10% BW support. In other words, they used the machine to their advantage. This could have been achieved by optimizing stride length versus cadence patterns to reach an optimal device-specific movement economy or by using the horizontal support that the zipped shorts can offer at waist level (leaning backwards on the shorts/canopy area while running). Horizontal forces contribute significantly to the cost of running (8), and we have already reported that running in a LBPP treadmill at 100% BW allowed athletes to reach faster peak treadmill speeds compared with a regular treadmill (14). We have not assessed kinematic parameters and hence cannot provide a definitive explanation, but a study by McNeill et al. (26) addressed this issue by measuring $\dot{V}O_2$ adaptation to running in the same LBPP device. They could show that at 90% BW, 60 min of running at a comfortable pace was sufficient to lower $\dot{V}O_2$ by 10.7%. We therefore can assume that our runners benefited from a similar adaptation, although their running speeds were a lot higher than that in the study by McNeill et al. (26).

$\dot{V}O_{2max}$. We could show a slight positive change in $\dot{V}O_{2max}$ (+1.9% in LBPP, +3.5% in CON). HIIT programs at v$\dot{V}O_{2max}$ can improve $\dot{V}O_{2max}$ capacity, but it remains unclear to which extent, as other studies have found conflicting results, either positive (12,37) or negative (4,11,13). It has been postulated that the time spent at or near $\dot{V}O_{2max}$ is important to improve, and various protocols have looked at optimal interval regimens to maximize this time in training (5,6,36). Intervals at 100% $v\dot{V}O_{2max}$ allow prolonged time at or near $\dot{V}O_{2max}$ but will primarily exert a stimulus on central factors (stroke volume), which is reflected in our study by lower submaximal HR after training. Billat et al. (5,6) have shown that shorter intervals (15–30 s) with active recovery can offer even longer time spent at or near $\dot{V}O_{2max}$ and might hence be better to improve peripheral cellular factors (capillarization, mitochondrial oxidative capacity). On the other hand, additional muscle power factors play a role in running performance improvement, such as neuromuscular and anaerobic properties related to muscle contraction (33). Midgley et al. (28) reviewed the evidence for training recommendations to increase $\dot{V}O_{2max}$ and concluded that intensity close to $\dot{V}O_{2max}$ is essential because duration of exercise at or above $\dot{V}O_{2max}$ has repeatedly been shown to be higher when interval strategies are used at speeds close or equal to $v\dot{V}O_{2max}$ (6,10). These authors concluded that speeds may need to be slightly sub- or supramaximal to $v\dot{V}O_{2max}$ but that the available scientific knowledge is insufficient to identify the most effective training methods. Well-trained runners may already have maxed out on their $\dot{V}O_{2max}$ potential, but as Kohn et al. (19) have shown, Type II muscle fiber lactate dehydrogenase activity benefits from HIIT sessions and might contribute to performance improvement in spite of stable $v\dot{V}O_{2max}$.

Speed at anaerobic threshold (vAT). Both groups improved vAT (+5.6% in CON, +7.4% in LBPP). Interval training programs have proven effective in improving lactate or ventilatory thresholds, although the optimal training intensity remains a matter of debate. Poole and Gaesser (34) could show that the greatest improvement in ventilatory and lactate thresholds happened after training at 105% of $v\dot{V}O_{2max}$, but studies have shown that intensity close to or above vAT can improve it consistently (25). Our findings match those reported by others in similar treadmill protocols (11,12,36), although Billat et al. could not show improvements in their elite runners (4).

RE. Many strategies have been investigated for improvement in RE, but it is not yet clear which works the best. Certainly, training history and volume are important (running is required to improve economy) (30), but various HIIT protocols, lower leg strength training, and plyometrics or altitude training could bring positive changes in RE. Neuromuscular recruitment capacity seems to play a major role, and HIIT programs with shorter intervals work better for RE improvement (18). In our study, the improvements in $v\dot{V}O_{2max}$ with subtle changes in $\dot{V}O_{2max}$ in our two groups would potentially indicate a better RE, which we did not observe. These positive changes could be brought by improved neuromuscular and anaerobic factors at high running speed, which were not tested. Changes in RE after a short (4–6 wk) HIIT program are inconsistent, with some studies showing improvement (4,11) and others are not (24). All of these training studies have a small number of participants (<10), and this may be a reason for the variation in training responses. In general, longer training programs seem to be more effective for RE (20). In addition, the age of participants may be of significance, as RE seems to naturally improve with running volume and years, hence making it harder to improve in our group of runners of a mean age of 34.7 (30). Both groups showed a relative nonsignificant increase in RE of 2.7% (LBPP) and 2.3% (CON), maybe pointing to a Type II error due to our small sample.

Submaximal HR. This parameter improved significantly in both groups (−2%), as could be shown by Kohn et al. (22) in their 6-wk similar HIIT study with endurance athletes, and has been described before (1,23). The mechanisms point to more oxygen delivered per heart beat (O_2 pulse increase), which means an increase in stroke volume after training. This central mechanism is dissociated from peripheral muscle adaptation, which leads to increased oxygen uptake efficiency (or RE).

Time to exhaustion. When we look at time to exhaustion at $v\dot{V}O_{2max}$ (T_{lim}), a similar pattern is present, although the 32% improvement in CON is nonsignificant. LBPP shows an important 92% T_{lim} increase after training (tested at pretraining $v\dot{V}O_{2max}$). Smith et al. (37) reported a similar 33% increase in T_{lim}; Esfarjani and Laursen (12), a 35% increase; Ferley et al., a 62% increase; whereas Billat et al. (4) did not report such an increase but they measured posttraining T_{lim} at the higher posttraining $v\dot{V}O_{2max}$. Denadai et al. (11) also did not measure improvements in T_{lim}, although they did not report which $v\dot{V}O_{2max}$ they used to assess T_{lim} after training (4,11–13,37). We also interpreted the larger improvements in LBPP as partly an adaptation that is device specific and beyond training-induced physiological changes.

The LBPP interval sessions, which were run at the same speed throughout the protocol, could have gotten easier as sessions went by, as discussed previously and shown by McNeill et al. (26). RPE recorded for each interval throughout the study decreased for all runners at the end of the program, albeit without difference between groups. LBPP runners seemed however to have more facility repeating training sessions, showing progressively less apprehension before the sessions. A few sessions in the CON group had to be delayed by 24 or 48 h because of excessive leg stiffness or soreness, which was never the case in the LBPP group, and one runner in CON dropped out because of newly occurring anterior knee pain. Although this was not measured, LBPP runners might have been training at lower percentages of their planned maximal $\dot{V}O_2$ after a few sessions. It would have been interesting to verify $\dot{V}O_2$ uptake during the intervals in both groups to test this hypothesis. If true, it would mean that the LBPP runners, despite a potentially lower overall metabolic stimulation during their training, still attained similar field performance improvements. It is premature to conclude that aside from metabolic stimulation, other mechanisms might have played a role, but there certainly is room to consider an effect of the higher speeds used thanks to the 10% BW reduction. The effect might be on neuromuscular capability, or on psychological factors, as it is acknowledged that mental limitations play a role in performance; lifting speed barriers may have benefited their field performance. These are hypotheses that would need to be investigated further to better understand the optimal use of LBPP treadmills for performance enhancing purposes in runners.

HIIT has been shown to be a very effective way to train endurance runners and obtain performance gains. Many variations around interval duration, intensity (speed), and recoveries have been investigated, and no specific training combination emerges as the optimal one. As is usually the case, a mix of various stimulations at different time points will provide improved training effects, which has been labeled "polarized" training by Seiler and Kjerland (35), and the individual athlete may respond differently to each HIIT combination.

Limitations. Some limitations need to be acknowledged in this study. First, the LBPP group did their pre- and postlaboratory performance measurement on the antigravity treadmill only. It was necessary to determine device-specific $v\dot{V}O_{2max}$ and T_{lim}, but to look at the effects on usual laboratory parameters, it would have been interesting to have supplemental tests done before and after on a regular treadmill. This would have added four maximal tests (two times $\dot{V}O_{2max}$ and two times T_{lim}). Second, our small sample size did not permit the analysis of small size effects on some performance parameters, and it would be interesting to conduct such training studies with a larger cohort but also with more experienced high-level athletes.

CONCLUSIONS

Eight sessions of HIIT over 4 wk improves running performance in well-trained runners, whether the training was done on a regular treadmill or on an LBPP (antigravity) treadmill, effectively reducing the runner's weight by 10% and allowing intervals to be run for a longer duration at a higher speed. Running performance improves with HIIT sessions on the LBPP treadmill, which could therefore offer an alternative training opportunity for sports involving running.

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