Effect of High-Intensity Resistance Training on Performance of Competitive Distance Runners

Ryan J. Hamilton, Carl D. Paton, and William G. Hopkins

In a recent study competitive road cyclists experienced substantial gains in sprint and endurance performance when sessions of high-intensity interval training were added to their usual training in the competitive phase of a season. The current study reports the effect of this type of training on performance of 20 distance runners randomized to an experimental or control group for 5 to 7 weeks of training. The experimental group replaced part of their usual competitive-phase training with 10 × 30-minute sessions consisting of 3 sets of explosive single-leg jumps (20 for each leg) alternating with 3 sets of resisted treadmill sprints (5 × 30-second efforts alternating with 30-second recovery). Before and after the training period all runners completed an incremental treadmill test for assessment of lactate threshold and maximum running speed, 2 treadmill runs to exhaustion for prediction of 800- and 1500-m times, and a 5-km outdoor time trial. Relative to the control group, the mean changes (±90% confidence limits) in the experimental group were: maximum running speed, 1.8% (± 1.1%); lactate-threshold speed, 3.5% (±3.4%); predicted 800-m speed, 3.6% (± 1.8%); predicted 1500-m speed, 3.7% (± 3.0%); and 5-km time-trial speed, 1.2% (± 1.1%). We conclude that high-intensity resistance training in the competitive phase is likely to produce beneficial gains in performance for most distance runners.

Key Words: athlete, incremental test, interval training, time trial

High-intensity resistance training enhances endurance performance in previously untrained individuals. Such training also appears to enhance the performance and physiological capacities of athletes when added to a program of low-intensity, high-volume base training in noncompetitive phases of the season. In a series of related studies Hoff and coworkers reported that high-intensity resistance training led to substantial improvements (2% to 5%) in cross-country-skiing performance. Enhancements in 5-km running time and 40-km cycling time have also been reported after periods of sport-specific resistance training with well-trained cross-country runners and cyclists. Whether high-intensity resistance training enhances endurance performance of athletes in later phases of the season is less clear, because

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athletes normally increase the intensity of training and make substantial improvements in performance as they progress toward the competitive phase.  

There have been only 2 published studies of performance after addition of high-intensity resistance training in the competitive phase. Toussaint and Vervoorn\(^9\) reported that 10 weeks of regular high-intensity resistance training improved race performance time by ~1% in national-level competitive swimmers. More recently Paton and Hopkins\(^10\) reported major gains (4% to 9%) in several measures of endurance power with a novel high-intensity resistance-training program implemented during a competitive phase. The athletes in that study were well-trained cyclists who completed 12 \(\times\) 30-min sessions consisting of sets of explosive leg jumps alternating with sets of high-resistance cycling sprints. The purpose of the current study was to determine the effects of a similar training program on performance with endurance runners during a competitive phase of their season.

### Methods

#### Design

The study was a controlled trial in which match-paired subjects were assigned to either an experimental or a control group based on peak running speed from a pre-training incremental exercise test. Subjects performed a set of exercise-performance tests in the 2 weeks before and after a 5- to 7-week training period. The study was performed during the competitive phase of a winter running season.

#### Subjects

Runners were recruited from local-club running events and training sessions. Criteria for involvement in the study were being male, age 17 to 40 years, and capable of running 5 km in under 20 minutes; engaging in a minimum of 30 km training per week; and regularly competing in road or cross-country running events throughout the winter season. After being informed of any risks associated with participation, 20 runners gave their written informed consent in accordance with the institute’s ethics committee. Their characteristics and baseline measures are shown in Table 1. There were no withdrawals from the study.

#### Exercise Performance Tests

The set of tests consisted of a 5-km time trial, an incremental treadmill test, and 2 runs to exhaustion at fixed running speeds, all performed within 2 weeks and with at least 3 days between tests. The runs to exhaustion always followed the incremental test. Runners were instructed to refrain from hard physical activity for the 24 hours preceding the performance trials. All laboratory tests were performed on a calibrated treadmill (Powerjog, Mid Glamorgan, UK) in a temperature-controlled laboratory (20 °C, ~50% relative humidity).

The 5-km time trial was performed on a local off-road running track familiar to all the runners. The course was sheltered with heavy woods throughout the majority of the track. The profile of the course was undulating, with a hilly section in the first and last 500 m. Pretraining and posttraining trials were held under similar dry
environmental conditions at temperatures of 9 to 14 °C. Runners were required to go through their usual competition warm-up and began the time trial at 1-minute intervals. The runners were seeded slowest to fastest based on their personal best 5-km time in the previous 2 seasons. Runners were instructed to treat the time trial as a race and complete the course as quickly as possible. Time for the 5 km was recorded with a stopwatch. After completing all pretraining tests, the runners were advised that the posttraining 5-km time trial would be considered a competition, and monetary prizes were awarded for the most improved runners. To avoid bias the prize pool was divided equally between the 3 most improved runners in each of the experimental and control groups.

For the incremental test, runners initially performed an 8-minute warm-up at 10 km/h followed by 5 minutes of passive recovery. Thereafter runners performed a submaximal incremental test consisting of four to six 3-minute stages at a 1% gradient and initial speed of 10 km/h. The speed of the treadmill was increased by 2 km/h for each subsequent stage. A 1-minute passive recovery between stages allowed for the collection of capillary-blood samples from the fingertip, which were

Table 1 Characteristics and Baseline Measures of the Runners, Mean ± SD

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Experimental group (n = 10)</th>
<th>Control group (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>age (y)</td>
<td>28 ± 8</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>body mass (kg)</td>
<td>72 ± 11</td>
<td>73 ± 10</td>
</tr>
<tr>
<td>height (cm)</td>
<td>178 ± 6</td>
<td>178 ± 11</td>
</tr>
<tr>
<td>competitive experience in distance running (y)</td>
<td>6.2 ± 4.7</td>
<td>8.5 ± 8.4</td>
</tr>
<tr>
<td>best 5-km time in previous 2 yr (min)</td>
<td>18.1 ± 1.8</td>
<td>17.7 ± 1.6</td>
</tr>
<tr>
<td>training volume in previous 4 wk* (h/wk)</td>
<td>3.6 ± 0.5</td>
<td>3.9 ± 1.4</td>
</tr>
<tr>
<td>VO2max (ml · kg−1 · min−1)</td>
<td>66 ± 7</td>
<td>66 ± 3</td>
</tr>
<tr>
<td>Baseline measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak running speed (km/h)</td>
<td>20.5 ± 1.3</td>
<td>20.4 ± 1.0</td>
</tr>
<tr>
<td>running speed at 4 mM lactate (km/h)</td>
<td>14.7 ± 2.0</td>
<td>15.5 ± 1.3</td>
</tr>
<tr>
<td>running speed at fixed heart rate (km/h)</td>
<td>14.2 ± 0.8</td>
<td>14.3 ± 0.9</td>
</tr>
<tr>
<td>fixed heart rate for the above (min)</td>
<td>154 ± 8</td>
<td>162 ± 12</td>
</tr>
<tr>
<td>predicted 800-m time† (min)</td>
<td>2.21 ± 0.11</td>
<td>2.22 ± 0.11</td>
</tr>
<tr>
<td>predicted 1500-m time† (min)</td>
<td>4.63 ± 0.25</td>
<td>4.60 ± 0.32</td>
</tr>
<tr>
<td>5-km time-trial time (min)</td>
<td>18.8 ± 1.3</td>
<td>18.3 ± 1.2</td>
</tr>
<tr>
<td>thigh cross-sectional area (cm²)</td>
<td>170 ± 31</td>
<td>174 ± 26</td>
</tr>
</tbody>
</table>

*Only 11 subjects provided adequate data for assessment.
†For treadmill running with a slope of 2%. Reduce times by ~10% for running on the flat.
immediately analyzed for whole-blood lactate using an automated analyzer (YSI 1500 Sport, Yellow Springs, Ohio). Each runner continued with the incremental stages until blood lactate concentration exceeded 4 mmol/L. The runner then continued with further increments of 1 km/h per 1-minute stage until exhaustion. Peak running speed was determined as the speed of the final completed stage plus the completed fraction of the next stage. During the pretraining incremental test, oxygen uptake was continuously measured with a calibrated metabolic cart (Vmax 29, SensorMedics, Yorba Linda, Calif). Maximum oxygen consumption was determined as the highest 20-s average recorded during the test. An equipment malfunction during the training period prevented the collection of oxygen-consumption data during the posttraining tests.

Two other measures of performance were derived from the incremental test. Speed at a blood lactate concentration of 4 mmol/L was predicted from log-log plots of blood lactate versus running speed\textsuperscript{11} using the trend function in Microsoft Excel separately for the pretraining and posttraining data. Speed at a fixed heart rate was determined in a similar fashion from linear plots of heart rate versus running speed. The fixed heart rate was determined for each runner as the average heart rate during the final minute of the middle 3-minute stage of the pretraining incremental test (or the mean of the 2 middle stages for runners who completed an even number of stages).

Three to five days after the incremental test and following the same warm-up procedure as described for the incremental test, runners performed 2 runs to exhaustion at a gradient of 2% and speeds of 110% and 90% of pretraining peak running speed. Time for each run was measured with a stopwatch. No information about elapsed time or distance was available to the athletes during the runs. A rest period of 15 minutes separated each 2 consecutive runs. Times to exhaustion were converted to a distance covered, and then the trend function in Microsoft Excel was used to predict 800-m and 1500-m times from the log-transformed distances and times.\textsuperscript{12}

Immediately before the runs to exhaustion, midthigh circumference and skinfold thickness were measured in accordance with ISAK guidelines\textsuperscript{13} and used to calculate nonskinfold cross-sectional area of the thigh (cm\textsuperscript{2}) using the following formula: \[\pi(C/2\pi - S/2)^2,\] where \(C\) = thigh circumference and \(S\) = skinfold thickness.

**Training**

Runners were requested to keep a record of their weekly training and competition hours for the duration of the study, but only 11 provided adequate information for accurately assessing baseline training. For the training period all runners were issued a recording heart-rate-monitor strap (Polar Electro, Kempele, Finland), which they were requested to wear during training and competitions. Not every training session or competition was recorded, however, because some runners occasionally forgot to wear the strap. The straps recorded the date, time, and duration of exercise, as well as heart rate at 5-second intervals. Data from the heart-rate strap were used to determine each runner’s weekly training volume and intensity. Estimates of training intensity were based on the runner’s maximal heart rate from the peak-running-speed test and classified as high 85% to 100%, moderate 70% to 84%, and low <69% of maximal heart rate.
The control group was instructed to continue with their existing or planned training and competition program. During the intervention period the experimental group continued with their competition program but replaced part of their usual training with $10 \times 30$-min sessions of a combination of explosive and high-resistance interval-training sets. The training program was designed by the investigators based on observations of training performed by competitive athletes and reviews of previous resistance-training studies and following discussions with coaches and sport scientists. The aim was to develop a sport-specific strength-training routine that athletes were prepared to use in the competitive phase of the season. The training was performed in a controlled laboratory environment under the supervision of at least 1 of the researchers. The training sessions were preceded and followed by a 10-minute warm-up and cool-down, respectively, on a treadmill at a self-selected intensity. Each session was performed 1 to 3 times per week, depending on the runner’s availability, and consisted of 3 sets of maximal-effort single-leg jumps alternating with 3 sets of maximal-intensity treadmill running efforts. For the jump sets subjects performed 20 explosive 1-leg step-ups off a 40-cm box with the right leg followed by 20 jumps with the left leg over a total duration of 2 minutes. In the running sets subjects completed $5 \times 30$-s maximal-intensity running efforts on a treadmill set at a gradient of 5% and a speed of 65% of the runner’s peak running speed, with 30-second rest periods between repetitions. Additional resistance in the running phase of the training sessions was provided by means of an elasticized tether attached to the runner’s waist and anchored to the wall behind the treadmill. The tether allowed the subject to run at maximum or near-maximum effort throughout each interval. A load-measuring scale (Rapala 25, Minnetonka, Minn) was attached in series with the tether, and load was recorded at 3-second intervals during each 30-second running interval. A transition period of 2 minutes separated each 2 consecutive running and jump sets.

**Statistical Analyses**

Inferential statistics were based on interpretation of magnitude of effects, as described in an Invited Commentary in this issue. Briefly, mean effects of training and their 90% confidence limits were estimated with a spreadsheet via the unequal-variances $t$ statistic computed for change scores between pretests and posttests in the 2 groups. Each subject’s change score was expressed as a percentage of baseline score via analysis of log-transformed values, to reduce bias arising from nonuniformity of error. Errors of measurement and individual responses expressed as coefficients of variation were also estimated with the spreadsheet. The spreadsheet also computed quantitative and qualitative chances that the true effects were beneficial, trivial, and harmful when a value for the smallest worthwhile change was entered. We used a value of 0.5% for the performance measures, because it represents the smallest worthwhile enhancement for runners. We also assumed 0.5% was the smallest worthwhile change in speed at 4-mM lactate and at a fixed heart rate, because a 0.5% change in these measures would produce a 0.5% change in endurance performance in the absence of other factors affecting performance. We do not know the smallest worthwhile change in body mass or thigh cross-sectional area in relation to effects on running performance, so we did not qualitatively
interpret the magnitude of the changes of these variables. For each effect we have shown the qualitative assessment of the chances of benefit when the chances of benefit were >5% and the chances of harm <5%. We have used a similar approach for the chances of harm. Effects for which chances of benefit and harm were >5% were interpreted as unclear.

**Results**

**Training**

Training volumes before and during the period of resistance training in the experimental group were 3.6 ± 0.5 and 3.0 ± 0.8 h/wk, respectively (mean ± SD); in the control group the corresponding volumes were 3.9 ± 1.5 and 3.6 ± 1.7 h/wk. Recordings of training heart rates during the experimental period showed that the resistance-training group spent a greater proportion of time at high intensity (32% ± 15% vs 27% ± 15% of total time) and at low intensity (28% ± 15% vs 21% ± 8%), but less at moderate intensity (41% ± 10% vs 51% ± 12%). The absolute time spent at the high and moderate intensities was higher in the control group (data not shown) because of the overall higher weekly volume in this group.

Figure 1 shows the mean load in the tether during the treadmill sprints for each of the 10 resistance-training sessions. The load increased by ~18% and appeared to stabilize by the ninth session, but there was a further increase of ~6% in the last session. The mean power (force × speed) developed against the tether in the first session was 231 W. Assuming that the metabolic energy cost of running was 3.86 J · m⁻¹ · kg⁻¹ with an efficiency of 25%, the mean power for running alone was 283 W, giving a total of 514 W. By the ninth session the total power output was 555 W, an increase of 7.0%.

![Figure 1](image)

*Figure 1* — Mean load in the tether during the 15 treadmill sprints of each training session for the experimental group. Values are means; bar is SD for a given session.
Effects on Performance

Table 2 shows the mean changes in performance and related measures for the experimental and control groups and statistics for the difference in the changes. There were clear-cut beneficial effects on all measures of performance except running speed at a fixed heart rate.

All coefficients of variation representing individual responses had uncertainties that were too large for any firm conclusions to be made (lower 90% confidence limits –6.1% to –0.8%, upper 90% confidence limits 1.4% through 5.2%). Standard errors of measurement for the control group between pretest and posttest, in order of increasing error, were 5-km speed, 0.8%; body mass, 0.8%; peak incremental speed, 1.1%; thigh cross-sectional area, 1.2%; 800-m speed, 1.7%; speed at fixed heart rate, 2.8%; 1500-m speed, 2.9%; and 4-mM lactate speed, 3.6%. The 90% confidence limits for the true values of the error of measurement were x± 1.5 for all measures.

Discussion

The major finding in this study of runners is similar to that in our previous study of cyclists\(^\text{10}\): replacing part of normal competitive-season training with sessions of high-intensity interval and explosive resistance training produced substantial gains in performance. The gains were unlikely to have resulted from a placebo effect,

Table 2  Changes in Performance and Anthropometric Measures in Experimental and Control Groups and Qualitative Inferences About the Effects on Competitive Performance*

<table>
<thead>
<tr>
<th>Change in Measure (%)</th>
<th>Experimental mean ± SD</th>
<th>Control mean ± SD</th>
<th>Difference; ±90% CL†</th>
<th>Qualitative inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted 800-m speed</td>
<td>4.4 ± 2.3</td>
<td>0.8 ± 2.4</td>
<td>3.6; ±1.8</td>
<td>Benefit almost certain</td>
</tr>
<tr>
<td>Predicted 1500-m speed</td>
<td>4.1 ± 3.6</td>
<td>0.4 ± 4.1</td>
<td>3.7; ±3.0</td>
<td>Benefit very likely</td>
</tr>
<tr>
<td>Peak incremental speed</td>
<td>2.7 ± 1.4</td>
<td>0.9 ± 1.5</td>
<td>1.8; ±1.1</td>
<td>Benefit very likely</td>
</tr>
<tr>
<td>Speed at 4-mM lactate</td>
<td>4.0 ± 2.7</td>
<td>0.5 ± 5.2</td>
<td>3.5; ±3.4</td>
<td>Benefit likely</td>
</tr>
<tr>
<td>5-km time-trial speed</td>
<td>2.2 ± 1.7</td>
<td>1.0 ± 1.1</td>
<td>1.2; ±1.1</td>
<td>Benefit likely</td>
</tr>
<tr>
<td>Speed at fixed heart rate</td>
<td>1.6 ± 4.7</td>
<td>–0.5 ± 4.0</td>
<td>2.1; ±3.4</td>
<td>Unclear</td>
</tr>
<tr>
<td>Body mass</td>
<td>0.2 ± 1.6</td>
<td>–1.0 ± 1.1</td>
<td>1.1; ±1.1</td>
<td>—</td>
</tr>
<tr>
<td>Thigh cross-sectional area</td>
<td>1.4 ± 1.7</td>
<td>–1.2 ± 1.8</td>
<td>2.6; ±1.3</td>
<td>—</td>
</tr>
</tbody>
</table>

* Effects are listed in order of decisiveness.
†±90% CL: Add and subtract this number to the mean effect to obtain the 90% confidence limits for the true difference.
because the effect on 1 of the submaximal measures of performance (4-mM lactate speed) was reasonably clear. Furthermore, the control group showed improvements in performance in almost all measures, so the net gains in performance were not simply a consequence of less effort by the control group in the posttest. Finally, the estimate of the effect was unlikely to be biased by any differences in fitness between the groups, which showed similar mean values at baseline for most measures.

The errors of measurement of most of the tests were comparable to those of some of the best tests of endurance performance, but the errors for the 2 submaximal physiological measures of performance would be too large for study of smallest worthwhile changes in performance, even allowing for the uncertainty in the estimates of error. The effect of the experimental training on the speed at a fixed heart rate was unclear because of the relatively large error of measurement.

Overall, the effects on performance in the current study (1.2% to 3.7%) were smaller than in our previous study (3.7% to 8.7%). Estimates in both studies are sufficiently precise to conclude that at least some of these differences are real rather than simply a consequence of sampling variation. We can think of several possible explanations for the differences. First, the competitive-season training of the runners was focused on cross-country events, which were of shorter duration and higher intensity than the road races of the cyclists. The experimental training might, therefore, have been less beneficial for the runners, because their usual training and competing would already have included some high-intensity intervals. Second, the use of a tether to increase resistance with treadmill running must have increased eccentric loading at the start of each footfall, whereas the extra resistance with cycling was achieved without any eccentric loading. Eccentric exercise produces muscle damage that could partly offset the beneficial effect of the concentric loading. Finally, the runners experienced what appeared to be a small gain in body mass, and the increase in thigh cross-sectional area indicates that the extra mass might have arisen from an increase in muscle mass in the legs. Extra mass produces a much greater increase in the metabolic cost of running when added to the legs than when added to other parts of the body, whereas any gain in leg mass of the cyclists after high-resistance training would presumably have little or no effect on the cost of cycling.

The difference in performance gains between the runners and cyclists in the 2 studies is consistent with the difference in the improvement in power output in the sprint-training bouts: 7% for the runners versus 13% for the cyclists after a comparable number of training sessions (Figure 1 in Paton and Hopkins). The time course of adaptation to the high-resistance interval training was also similar in the 2 studies, reaching a plateau by the eighth training session. There was a further substantial increase in the last training session with the runners, but this effect probably resulted from motivation. We cannot exclude the possibility of gains continuing at a slower rate beyond 10 training sessions, but whether athletes will tolerate a longer period of such physically demanding training is unclear.

The malfunction in our expired gas equipment meant that we were unable to directly address possible mechanisms for the performance enhancement, but it is already reasonably clear from previous studies that high-intensity resistance training enhances aerobic power of athletes at least partly via an increase in aerobic economy. If this were the mechanism responsible for the improvements in performance in the present study, there should have been greater enhancement in the
5-km time trial than for predicted 800-m speed, which would have less contribution from aerobic power. Although the uncertainty in the estimates is consistent with a gain of ~2% for both these measures, it is likely that there was less enhancement for the longer test. The 5-km time trial was a self-paced test, however, so it is possible that the runners showed less enhancement in this test because they did not choose a pace appropriate for their new state of fitness. Alternatively, the resistance training might have had a greater effect on the anaerobic component of endurance performance, possibly via biomechanical adaptations.6

In conclusion, 10 sessions of high-intensity resistance training produced worthwhile gains in performance of well-trained runners in a competitive season. Further research is needed to clarify the mechanisms responsible and to investigate ways to increase the efficacy of the training.

References