# The Effects of Uphill vs. Level-Grade High-Intensity Interval Training on VO2max, VMax, VLT and TMax in Well-Trained Distance Runners.

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# The Effects of Uphill Vs. Level-Grade High-Intensity Interval Training on $\dot{V}O_2max$, $V_{MAX}$, $V_{LT}$, and $T_{MAX}$ in Well-Trained Distance Runners

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## Abstract

Ferley, DD, Osborn, RW, and Vukovich, MD. The effects of uphill vs. level-grade high-intensity interval training on $\dot{V}O_2max$, $V_{max}$, $V_{LT}$, and $T_{max}$ in well-trained distance runners. *J Strength Cond Res* 27(6): 1549–1559, 2013—Uphill running represents a frequently used and often prescribed training tactic in the development of competitive distance runners but remains largely uninvestigated and unsubstantiated as a training modality. The purpose of this investigation included documenting the effects of uphill interval training compared with level-grade interval training on maximal oxygen consumption ($\dot{V}O_2max$), the running speed associated with $\dot{V}O_2max$ ($V_{max}$), the running speed associated with lactate threshold ($V_{LT}$), and the duration for which $V_{max}$ can be sustained ($T_{max}$) in well-trained distance runners. Thirty-two well-trained distance runners (age, 27.4 ± 3.8 years; body mass, 64.8 ± 8.9 kg; height, 173.6 ± 6.4 cm; and $\dot{V}O_2max$, 60.9 ± 8.5 $ml \cdot min^{-1} \cdot kg^{-1}$) received assignment to an uphill interval training group ($G_{Hill}$ = 12), level-grade interval training group ($G_{Flat}$ = 12), or control group ($G_{Con}$ = 8). $G_{Hill}$ and $G_{Flat}$ completed 12 interval and 12 continuous running sessions over 6 weeks, whereas $G_{Con}$ maintained their normal training routine. Pre- and posttest measures of $\dot{V}O_2max$, $V_{max}$, $V_{LT}$, and $T_{max}$ were used to assess performance. A 3 × 2 repeated measures analysis of variance was performed for each dependent variable and revealed a significant difference in $T_{max}$ in both $G_{Hill}$ and $G_{Flat}$ ($p < 0.05$). With regard to running performance, the results indicate that both uphill and level-grade interval training can induce significant improvements in a run-to-exhaustion test in well-trained runners at the speed associated with $\dot{V}O_2max$ but that traditional level-grade training produces greater gains.

**Key Words** hill running, incline running, sprinting, treadmill running

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## Introduction

Uphill running represents a frequently prescribed and often used form of high-intensity interval training in the development of competitive distance runners. For example, a survey of teams competing in the 1996 National Collegiate Athletic Association Division I national cross-country meet verified its widespread use as a training method and revealed that uphill training correlated with faster team times (29). Moreover, references to its potential effectiveness as a high-velocity resistance-to-movement exercise have appeared in scholarly reviews (2,36). Although widely touted by coaches, athletes, and industry lay journals as a means to increase lower-body power output and running speed–and ultimately race performance–interestingly, a review of the literature produced just one study examining the physiological responses to uphill training for distance runners (24).

With the physiological effects of uphill training on distance running performance remaining essentially unproven, its purported mechanisms of action for improving running performance have been proposed to be similar to other high-intensity resistance-to-movement training tactics such as explosive strength training, heavy strength training, and plyometric training. Recent investigations suggest that these types of training methods improve distance running performance by enhancing muscular and neuromuscular characteristics, which ultimately lead to improved economy of movement (28,42,47,51). However, as opposed to other high-intensity resistance-to-movement exercises, uphill running can be seen to represent a much more sport-specific training tactic and may therefore prove more effective at improving distance running performance than other high-intensity resistance-to-movement exercises. In comparison, traditional level-grade high-intensity interval training using at or near maximum intensities has long been recognized for its potent and robust effects on improving physiological indices such as $\dot{V}O_2max$, blood lactate kinetics, and muscle buffer capacity in already well-trained distance runners (6,8,31). As a result, improvements in indices such as those just mentioned may manifest themselves during actual training and racing as both a greater time spent at or near $\dot{V}O_2max$ and a greater amount of work being completed at a high intensity (7). Improving through training the time spent at or near $\dot{V}O_2max$ or the amount of work completed at a high intensity appears crucial as the ability to sustain near maximum efforts in distance running correlates strongly with running performance in events ranging from 800 m to 10 km (3,6,39).

Earlier research has revealed that when seeking to improve the running performance of well-trained distance runners, training velocities that elicit at least 90% $\dot{V}O_2max$ must be used (37,45). Whereas explosive strength training, heavy strength training, and plyometric training incorporate resistance-to-movement exercises such as weighted squat jumps, knee extensions, and single leg bounds that involve a percentage of 1 repetition maximum or body weight, at present, no recommendations exist for prescribing training intensities when performing uphill running. One possible training intensity to use in uphill running may be the running velocity associated with $\dot{V}O_2max$, which in terms of level-grade interval running represents a training intensity that has been the focus of many investigations. Termed $V_{max}$, this training intensity can be determined in an incremental running test and may lead to greater improvements in $\dot{V}O_2max$ through a variety of means, including increased mitochondrial density and enhanced lactate removal (2,6,16).

Bout duration represents the other main facet to interval training, and, similar to training intensity, at present, no recommendations exist for prescribing bout durations when performing uphill running. In contrast, previous investigations into level-grade interval training show both short bouts ranging 10 to 30 seconds and long bouts lasting up to 5 minutes can be effective for enhancing the physiological determinants associated with distance running performance (31,35). Regardless, similar to $V_{max}$, 2 key considerations for interval length selection must include attempts to maximize both the time spent at $\dot{V}O_2max$ and the total work completed at a high intensity (7). Hence, pursuits to optimize these 2 criteria and to individualize interval training protocols have led to recent investigations examining the time to exhaustion while running at the velocity associated with $\dot{V}O_2max$ (21–23,49,50). This duration, defined previously as $T_{max}$, has been shown to be highly variable among runners with the same $V_{max}$ (21) and therefore provides a physiological rationale for prescribing individualized bout durations when performing interval work. In attempts to maximize both the time spent at $\dot{V}O_2max$ and the total work completed at $\dot{V}O_2max$, previous findings suggest that bout durations of 60% $T_{max}$ appear most effective (21,22,49,50).

Because many coaches, distance runners, and industry pundits advocate uphill training as part of a comprehensive distance running training routine despite a lack of proven recommendations for training intensity, bout duration, hill grade, and evidence as to its overall physiological effectiveness, we sought to conduct an investigation comparing this mode of training with traditional level-grade high-intensity interval training. Therefore, the purpose of this study included documenting, in well-trained athletes, the physiological effects associated with high-intensity interval training performed during uphill running on a 10% grade compared with level-grade running while using previously established training prescriptors for running intensity and bout duration. We hypothesized that both uphill high-intensity interval training at a 10% grade and high-intensity interval training performed on a level-grade would result in significantly improved $\dot{V}O_2max$, velocity at lactate threshold ($V_{LT}$), velocity at $\dot{V}O_2max$ ($V_{max}$), and time to exhaustion ($T_{max}$) compared with a group of controls but that physiological gains from level-grade running would be more pronounced.

## Methods

### Experimental Approach to the Problem

A parallel, 3-group, longitudinal (pretraining, posttraining) study approach was used. Before the start of the study, the investigator asked each participant his or her willingness to be randomly assigned to 1 of 3 groups: hill interval training, $G_{Hill}$; level-grade interval training, $G_{Flat}$; or control group in which each participant maintained his or her normal training routine, $G_{Con}$. Those participants unwilling to participate in $G_{Hill}$ or $G_{Flat}$ training methods received assignment to the control group ($G_{Con} = 8$) while all other participants were matched according to $\dot{V}O_2max$ and then randomly assigned by the investigator to the hill interval training group ($G_{Hill} = 12$) or the level-grade interval training group ($G_{Flat} = 12$). The study took place at Avera Sports Institute (Sioux Falls, SD) from January to August 2011 and consisted of (a) familiarization training, (b) pretraining testing, (c) a 6-week training intervention, and (d) posttraining testing.

### Subjects

In addition to contacting members of a local running club, the principal investigator also recruited potential participants through social media. Thirty-two well-trained participants (14 men and 18 women) voluntarily enrolled and gave their written consent to participate in this study after being fully informed of the risks and discomforts associated with the experimental procedures. Inclusion criteria for male and female participants required having completed a 5 km run under 21:00 minutes and 24:00 minutes, respectively, within the previous 12 months. Female participants also completed a questionnaire regarding menstrual cycle status at the initial visit. The investigator excluded those individuals who had experienced a lower-body injury in the previous 3 months. The participants had the following characteristics (mean ± *SD*): age, 27.4 ± 3.8 years; body mass, 64.8 ± 8.9 kg; and height, 173.6 ± 6.4 cm. The Avera McKennan Hospital and University Health Center's Institutional Review Board approved this study, and it conformed to the recommendations of the Declaration of Helsinki.

### Procedures

*Familiarization Testing.* In the week before the start of the testing and training program, participants reported to Avera Sports Institute to become familiarized with a warm-up routine and $\dot{V}O_2max$ test. After the $\dot{V}O_2max$ test, the investigator explained the concepts of $V_{max}$, $V_{LT}$, and $T_{max}$. The participants completed the same warm-up routine before every testing and training session throughout the 6-week program. For all performance testing, the investigator instructed the participants to arrive in a rested and hydrated state and to avoid caffeine, alcohol, and strenuous exercise in the 2 days preceding a test session. Participants were also shown how to complete a food diary for the 3 days before baseline testing and asked to replicate this diet before the posttraining session. Additionally, attempts were made to ensure all participants completed pre- and posttesting procedures at approximately the same time of day. All testing days were separated by ≥48 hours.

*Performance Testing.* Within 7 days of completing the $\dot{V}O_2max$ test familiarization trial, participants undertook their performance tests. These performance tests took place on 2 separate days, with day 1 consisting of an incremental running test to determine $\dot{V}O_2max$, $V_{max}$, and $V_{LT}$ and day 2 testing involving a $T_{max}$ test. The $\dot{V}O_2max$ test consisted of using a Physio-Dyne MAX-II Metabolic Cart (AEI Technologies, Inc., Bastrop, TX, USA), which the investigator calibrated before each test, and having the participants complete 2-minute stages on a Super Treadmill (Standard Industries, Fargo, ND, USA) set to a 1% grade (7). The investigator modified the initial treadmill speed for each individual to determine a comfortable starting speed. At the completion of each 2-minute stage, a 30-second pause occurred at which time the investigator collected a fingertip blood sample by using a 2.0 × 1.5 mm BD Microtainer single-use contact-activated lancet (Becton, Dickinson and Co., Franklin Lakes, NJ, USA) and Lactate Plus portable lactate analyzer (Nova Biomedical, Waltham, MA, USA) (7). During each blood sample collection, the investigator prepared the fingertip by cleaning it with alcohol and drying it with a gauze pad using a sterile technique.

With each subsequent stage of the $\dot{V}O_2max$ running test, the investigator increased the treadmill speed by 0.8 km per hour. The investigator used the following criteria to determine the participant's $\dot{V}O_2max$: (a) a respiratory exchange ratio > 1.10, (b) an ending heart rate within $\pm 10\ b\cdot min^{-1}$ of age-predicted HRmax (220 − age) (18), (c) no further increase in $O_2$ consumption despite an increased work rate, and (d) volitional exhaustion. In determining $V_{max}$, the investigator required the participant to complete at least 90 seconds of the 2-minute stage; if the participant completed less than 90 seconds of the 2-minute stage, then $V_{max}$ was defined as the treadmill speed from the previous stage. Regarding blood lactate measurements, the investigator defined the participant's lactate threshold as that speed which elicited a $1\ mmol\cdot L^{-1}$ rise above baseline (12).

The assessment of $T_{max}$ took place on day 2 of performance testing, and after arriving at the training facility, the participants performed the same warm-up routine described above. After a 5-minute pause, the investigator set the Super Treadmill to a 1% grade and the participant's previously determined $V_{max}$ and the participant then mounted the Super Treadmill and ran as long as possible. During the $T_{max}$ test, each participant received verbal encouragement to run to volitional exhaustion. For both the $\dot{V}O_2max$ and $T_{max}$ tests, the investigator had the participants wear a heart rate monitor (Polar RS400 Heart Rate Monitor; Polar Electro Oy, Kempele, Finland). Heart rate data were collected in 5-second increments and downloaded to a personal computer after each testing session. Additionally, heart rate data were collected in a similar manner for $G_{Hill}$ and $G_{Flat}$ during each of the 4 weekly training sessions and downloaded to the same personal computer after each training session. Within 48–72 hours of the last training session, each participant repeated the day 1 testing procedures. After an additional 48–72 hours of rest, each participant repeated day 2 testing procedures.

*Training Protocol.* Before beginning the investigation, all participants regularly engaged in moderate-intensity run training 3–4 times per week; however, none routinely performed high-intensity interval training in the 3 months preceding the training intervention. During the training intervention, $G_{Hill}$ performed 2 high-intensity interval sessions and 2 continuous running sessions per week. $G_{Hill}$ high-intensity interval sessions consisted of completing 10–14 bouts for 30 seconds on a treadmill set to a 10% grade while running at 100% $V_{max}$. Additionally, rest durations between interval bouts lasted for the time it took heart rate to return to 65% of the individual's age-predicted maximum (65% HRmax). For the days on which continuous run training took place, $G_{Hill}$ participants ran on a treadmill set at 1% grade (to more closely replicate overground running) (27) and 75% $V_{max}$ for 45–60 minutes. $G_{Flat}$ also completed 2 high-intensity interval sessions and 2 continuous running sessions per week. $G_{Flat}$ high-intensity interval running sessions consisted of completing 4–6 bouts for a duration equal to 60% $T_{max}$ on a treadmill set to a 1% grade and 100% $V_{max}$. $G_{Flat}$ participants also used rest durations between interval bouts that lasted for the time it took heart rate to return to 65% HRmax. During each of the continuous running sessions, $G_{Flat}$ participants also ran for 45–60 minutes at a treadmill velocity and grade set to 75% $V_{max}$ and 1% grade,

**TABLE 1.** The 6-week training protocol for the 2 high-intensity interval training groups ($G_{Hill}$ and $G_{Flat}$) and the control group ($G_{Con}$).

| | Sessions per week | Bouts per session | Intensity | Work duration | Rest duration |
|---|---|---|---|---|---|
| $G_{Hill}$ | 2 | 10–14 | 100% $V_{max}$ | 30 s | 65% HRmax |
| | 2 | 1 | 75% $V_{max}$ | 45–60 min | NA |
| $G_{Flat}$ | 2 | 4–6 | 100% $V_{max}$ | 60% $T_{max}$ | 65% HRmax |
| | 2 | 1 | 75% $V_{max}$ | 45–60 min | NA |
| $G_{Con}$ | NA | NA | NA | NA | NA |

respectively. Participants in $G_{Con}$ continued their normal weekly training programs (4.9 ± 0.07 days per week, 270.4 ± 81.6 minutes per week) away from the training facility. During the 6-week training intervention, $G_{Con}$ completed daily training diaries, which the investigator analyzed at the end of the intervention.

All testing and high-intensity interval training sessions involved use of a Super Treadmill, which raises and lowers hydraulically, offers a running belt area measuring 51 × 183 cm, and has elevation and speed capacities ranging from −10 to 40% and 0 to 48 km per hour, respectively. On days the participants completed a continuous running session, they used a Precor, Inc. 932i treadmill (Woodinville, WA). The specifications of the Precor, Inc. 932i treadmill include a running belt area measuring 56 × 142 cm and elevation and speed capacities ranging from 0 to 15.0% and 0 to 19.3 km per hour, respectively. Calibration of all treadmills for speed and incline occurred weekly. The principal investigator administered and monitored all $G_{Hill}$ and $G_{Flat}$ high-intensity interval training sessions on the Super Treadmill and gave "spotting" assistance as a safety precaution when needed. Additionally, on days during which the testing and training sessions involved using the Super Treadmill, participants gathered real-time visual feedback on running form via a 91 × 183-cm wall-mounted mirror in front of the Super Treadmill. The 6-week group-assigned training protocol appears in Table 1.

### Statistical Analyses

For all data analyses, the investigator used the statistical analysis program JMP (v.8.0.2; SAS Institute, Cary, NC, USA). Descriptive statistics of each outcome variable, including mean, standard deviations, and tests of normality were determined. All dependent variables ($\dot{V}O_2max$, $V_{max}$, $V_{LT}$, and $T_{max}$) were assessed for percent change and analyzed with a 1-way analysis of variance to determine differences between groups. A mixed design repeated measures analysis of variance (3 × 2) was used to test for the effect of training and training group on $\dot{V}O_2max$, $V_{max}$, $V_{LT}$, and $T_{max}$. A significance level of $p \leq 0.05$ was set for all statistical analyses and, where significance was found, a Tukey post hoc test was performed.

## RESULTS

### Body Mass and $\dot{V}O_2max$

Table 2 highlights the training investigation's effect on body mass and $\dot{V}O_2max$. Both before and after the intervention, a significant difference existed in body mass between $G_{Con}$ and the 2 high-intensity training groups; however, no significant changes in body mass occurred in any of the groups or between groups in response to the training. Concerning $\dot{V}O_2max$, no significant differences existed between groups before or after training and no alteration in $\dot{V}O_2max$ occurred in any of the groups over the course of the 6-week investigation.

**TABLE 2.** Pre- vs. posttraining values for body mass and maximal oxygen uptake ($\dot{V}O_2max$).†

| | $G_{Hill}$ | $G_{Flat}$ | $G_{Con}$ |
|---|---|---|---|
| Body mass (kg) | | | |
| Pre | 65.8 ± 12.2 | 66.0 ± 7.1 | 62.6 ± 7.5* |
| Post | 65.3 ± 12.5 | 66.0 ± 6.9 | 62.3 ± 6.9* |
| % Δ | −0.1 ± 2.2 | 0.0 ± 1.3 | −0.6 ± 2.1 |
| $\dot{V}O_2max$ ($ml \cdot min^{-1} \cdot kg^{-1}$) | | | |
| Pre | 63.3 ± 8.0 | 59.4 ± 8.9 | 59.9 ± 8.6 |
| Post | 62.7 ± 7.0 | 59.6 ± 7.6 | 58.3 ± 7.9 |
| % Δ | −0.4 ± 8.1 | 0.8 ± 5.5 | −2.6 ± 3.9 |

*Significantly different from $G_{Hill}$ and $G_{Flat}$ both pre- and posttraining ($p < 0.05$).
†Data are mean (±*SD*).

### Total Weekly Exercise Dynamics

Table 3 highlights the differences among the 3 groups in total weekly exercise time. During each 2-week microcycle of the 6-week training intervention, $G_{Con}$ spent considerably more time exercising compared with $G_{Hill}$ and $G_{Flat}$ and this difference proved significant. In brief, $G_{Con}$ spent more than double the time exercising during each 2-week microcycle.

### High-Intensity Interval and Continuous Run Dynamics

Table 4 shows a comparison of the high-intensity interval

**TABLE 3.** A comparison of total weekly exercise dynamics.†

| Total weekly exercise time | $G_{Hill}$ | $G_{Flat}$ | $G_{Con}$ |
|---|---|---|---|
| Weeks 1 and 2 | | | |
| Interval run time (s) | 600 | 1,088 ± 73.4 | |
| Continuous run time (s) | 6,012 ± 492 | 5,736 ± 288 | |
| Total training time (s) | 6,612 ± 492 | 6,824 ± 361.4 | 14,313.8 ± 2,635.5* |
| Total training time (min) | ~110 ± 8.2 | ~114 ± 6.0 | ~238 ± 43.9 |
| Weeks 3 and 4 | | | |
| Interval run time (s) | 720 | 1,360 ± 73.4 | |
| Continuous run time (s) | 6,012 ± 492 | 5,736 ± 288 | |
| Total training time (s) | 6,732 ± 492 | 7,096 ± 361.4 | 17,151.3 ± 5,762.3* |
| Total training time (min) | ~112 ± 8.2 | ~118 ± 6.0 | ~285 ± 96.0 |
| Weeks 5 and 6 | | | |
| Interval run time (s) | 840 | 1,632 ± 73.4 | |
| Continuous run time (s) | 6,012 ± 492 | 5,736 ± 288 | |
| Total training time (s) | 6,852 ± 492 | 7,368 ± 361.4 | 17, 209.8 ± 7,562.5* |
| Total training time (min) | ~114 ± 8.2 | ~122 ± 6.0 | ~286 ± 126.0 |

*Significantly greater than $G_{Hill}$ and $G_{Flat}$ ($p < 0.05$).
†Data are mean (±*SD*).

training, continuous run training, and the total time commitment to weekly exercise. The interval length between $G_{Hill}$ and $G_{Flat}$ revealed a significant difference between the fixed bouts performed by $G_{Hill}$ and the average 60% $T_{max}$ bouts undertaken by $G_{Flat}$. Regarding the average recovery duration between bouts during the high-intensity interval sessions, both $G_{Hill}$ and $G_{Flat}$ participants rested for approximately the same time; however, the average work to rest ratio in $G_{Hill}$ (approximately 1:4) was significantly longer than the work to rest ratio in $G_{Flat}$ (approximately 1:1).

Additionally, further analyses of the high-intensity interval sessions revealed differences in weekly time spent running during interval training sessions between $G_{Hill}$ and $G_{Flat}$. The 6-week program was subdivided into three 2-week microcycles, and every 2 weeks, the number of high-intensity interval bouts increased in both groups. In weeks 1 and 2, weeks 3 and 4, and weeks 5 and 6, $G_{Hill}$ completed 10, 12, and 14 intervals, respectively, whereas during the same microcycles, $G_{Flat}$ performed 4, 5, and 6 intervals, respectively. During each 2-week microcycle, $G_{Flat}$ spent significantly more time running during interval training sessions compared with $G_{Hill}$. For example, during each of the three 2-week microcycles, $G_{Flat}$ spent nearly double the time running during interval training sessions.

**TABLE 4.** A comparison of high-intensity interval and continuous run dynamics.†

| | $G_{Hill}$ | $G_{Flat}$ | $G_{Con}$ |
|---|---|---|---|
| Interval length (s) | 30 | 136 ± 36.7 | NA |
| Recovery between intervals (s) | 135 ± 23.7 | 142 ± 45.4 | NA |
| Average work to rest ratio (s) | 1:4 | 1:1* | NA |
| Total interval time by week | | | |
| Weeks 1 and 2 | | | |
| (Sets × time) × days per week | (10 × 30) × 2 | (4 × 136) × 2 | NA |
| Total run time (s) | 600 | 1,088 ± 73.4* | |
| Total run time (min) | 10 | ~18 | |
| Weeks 3 and 4 | | | |
| (Sets × time) × days per week | (12 × 30) × 2 | (5 × 136) × 2 | NA |
| Total run time (s) | 720 | 1,360 ± 73.4* | |
| Total run time (min) | 12 | ~22 | |
| Weeks 5 and 6 | | | |
| (Sets × time) × days per week | (14 × 30) × 2 | (6 × 136) × 2 | NA |
| Total run time (s) | 840 | 1,632 ± 73.4* | |
| Total run time (min) | 14 | ~27 | |
| Average continuous run time | | | |
| Total run time per day (s) | 3,006 ± 246 | 2,868 ± 144 | NA |
| Total run time week (s) | 6,012 ± 492 | 5,736 ± 288 | |

NA = not applied.
*Significantly different from $G_{Hill}$ ($p < 0.05$).
†Data are mean (±*SD*).

An analysis of the continuous running sessions revealed that, on average, $G_{Hill}$ ran

**TABLE 5.** Pre- vs. posttraining values for $V_{max}$, $V_{LT}$, blood lactate at $V_{LT}$, final blood lactate concentration, and $T_{max}$.‡

| | $G_{Hill}$ | $G_{Flat}$ | $G_{Con}$ |
|---|---|---|---|
| $V_{max}$ ($km \cdot h^{-1}$) | | | |
| Pre | 17.3 ± 2.0 | 17.3 ± 2.1 | 17.5 ± 1.6 |
| Post | 17.8 ± 1.7 | 18.1 ± 2.3 | 18.0 ± 1.5 |
| % Δ | 2.8 ± 3.3 | 4.4 ± 4.6 | 2.9 ± 2.4 |
| $V_{LT}$ ($km \cdot h^{-1}$) | | | |
| Pre | 14.9 ± 1.9 | 15.3 ± 1.5 | 15.1 ± 1.4 |
| Post | 15.1 ± 1.7 | 15.4 ± 1.5 | 15.5 ± 1.2 |
| % Δ | 1.6 ± 3.5 | 1.0 ± 4.6 | 2.9 ± 4.9 |
| $BLa_{LT}$ ($mmol \cdot L^{-1}$) | | | |
| Pre | 5.2 ± 1.5 | 5.5 ± 1.3 | 4.9 ± 1.9 |
| Post | 4.5 ± 1.1 | 4.3 ± 1.0 | 4.4 ± 1.7 |
| % Δ | −9.2 ± 19.1 | −18.1 ± 21.1 | −8.4 ± 14.6 |
| $BLa_{max}$ ($mmol \cdot L^{-1}$) | | | |
| Pre | 11.8 ± 1.7 | 10.9 ± 2.7 | 11.2 ± 1.8 |
| Post | 13.3 ± 2.8 | 11.9 ± 2.6 | 11.6 ± 2.1 |
| % Δ | 12.0 ± 14.4 | 12.5 ± 27.5 | 0.4 ± 16.9 |
| $T_{max}$ (s) | | | |
| Pre | 223.0 ± 56.1 | 224.6 ± 64.0 | 269.1 ± 65.9 |
| Post | 293.1 ± 69.4* | 363.0 ± 116.6*† | 321.1 ± 35.3 |
| % Δ | 31.7 ± 16.0 | 61.9 ± 32.5 | 23.7 ± 22.1 |

*Significantly different from pre- to posttraining ($p < 0.05$).
†Significantly greater than $G_{Hill}$ ($p < 0.05$).
‡Data are mean (±*SD*).

slightly longer than $G_{Flat}$; however, this difference was not significant. As both $G_{Hill}$ and $G_{Flat}$ completed 2 continuous running sessions per week, the total weekly time commitment to continuous running by each group was determined, with no significant difference found between the 2 groups.

#### $V_{max}$, $V_{LT}$, Blood Lactate at $V_{LT}$, Final Blood Lactate Concentration, and $T_{max}$

Table 5 reveals the impact of training on $V_{max}$, $V_{LT}$, blood lactate concentration at $V_{LT}$ ($BLa_{LT}$), final blood lactate concentration ($Bla_{max}$), and $T_{max}$. Regarding $V_{max}$, all 3 groups experienced an increase in the running velocity associated with $\dot{V}O_2max$; however, none of these improvements were statistically significant. Additionally, all 3 groups experienced an increase in $V_{LT}$; however, none of these improvements were statistically significant.

Examining $BLa_{LT}$, each of the groups experienced a decrease in blood lactate concentration at the same initial running velocity associated with lactate threshold after training; however, none of these changes were significant. In terms of the final blood lactate concentration achieved during blood lactate testing, each group experienced an increase in $BLa_{max}$ after training; however, none of these changes were statistically significant.

Last, all 3 groups experienced an increase in time to fatigue while running at $V_{max}$. Specifically, $T_{max}$ increased by 68 seconds in $G_{Hill}$, 138 seconds in $G_{Flat}$, and 52 seconds in $G_{Con}$ or 31.7, 61.9, and 23.7%, respectively. In $G_{Hill}$ and $G_{Flat}$, the improvement in $T_{max}$ proved significant, whereas in $G_{Con}$, it did not.

## Discussion

As described above, the purpose of this study sought to examine the physiological effects associated with high-intensity interval training performed during uphill running on a 10% grade compared with level-grade running while using well-established training prescriptors for running intensity and bout duration. The major finding of the present investigation suggests that 6 weeks of either uphill or level-grade high-intensity interval training in already well-trained individuals can invoke physiological changes that lead to running for a significantly longer period at the velocity associated with $\dot{V}O_2max$.

Other findings regarding the indices measured included no change in $\dot{V}O_2max$ in any of the groups and trends toward improvements in $V_{max}$ and $V_{LT}$ in all groups, although these trends proved nonsignificant. As well, although nonsignificant, the $BLa_{LT}$ and $BLa_{max}$ of all participants trended lower and higher, respectively, after training. Furthermore, a comparison of the high-intensity interval bout dynamics between $G_{Hill}$ and $G_{Flat}$ revealed a significant difference in interval length that routinely led to $G_{Flat}$ performing nearly 2 times the work on every high-intensity interval training day. In terms of rest duration between interval bouts and the time for which it took heart rate to return to 65% HRmax, both $G_{Hill}$ and $G_{Flat}$ rested for approximately the same time; however, $G_{Hill}$ rested significantly longer than $G_{Flat}$ participants (i.e., greater than work to rest ratio). Last, a review of total weekly exercise time showed that $G_{Con}$ spent significantly more time exercising than either $G_{Hill}$ or $G_{Flat}$ during each of the three 2-week microcycles.

To the best of our knowledge, the present investigation represents the first study to document the effects of uphill training in a functional time-to-exhaustion running test at the speed associated with $\dot{V}O_2max$. Although uphill running represents a commonly used and often prescribed training tactic, our literature review produced just one previous investigation into the physiological effects associated with this mode of training. Performed by Houston and Thomson (24), the study involved 4 weekly outdoor training sessions for 6 weeks and incorporated a variety of hill grades and bout durations–and weight training–as a part of each training session. After the training intervention, despite no improvements in $\dot{V}O_2max$, the participants covered significantly greater distances during 60 and 90 second runs on a hill with a 3.3% grade and ran for a longer period on a treadmill set to 215 m per minute and 20% grade. Moreover, the participants experienced significant increases in resting adenosine triphosphate concentration and final blood lactate values (as measured in the uphill treadmill running test) and lifting greater loads during 15 repetition maximum leg press training.

Despite a paucity of evidence substantiating the physiological effectiveness of uphill training, several investigations have showcased the kinematics, kinetics, and electromyographical responses associated with both outdoor hill running and indoor incline treadmill running, which may give insights as to the impact of this mode of training on those competing in distance running events. Roberts and Belliveau (44) determined that virtually all increases in work output associated with running up increasingly steeper grades (on a specially built ramp) resulted from increased network done at the hip. Slawinski et al. (48) reported that running on an outdoor hill of approximately 5% grade compared with level-ground running resulted in slower peak running velocity, more flexed lower limb joint angles, and a significant decrease in hamstring activity. Swanson and Caldwell (53) investigated incline treadmill running at 4.5 m per seconds and 30% grade compared with level running at the same stride frequency (approximately 7.82 m per seconds) and found that incline running leads to greater muscle activation in lower-body musculature (except the hamstrings); increased joint power moments at the ankle, knee, and hip; and nearly identical sagittal plane kinematics. As well, they reported significantly higher angular velocities at the ankle, knee, and hip during the push-off phase in the incline condition, leading the authors to conclude that incline treadmill running represented both a mechanical and velocity-specific form of training.

Given that uphill running has been shown to be associated with increased lower-body kinetic output when compared with level-grade running at the same velocity, it appears that this mode of training has merit as a sport-specific resistance-to-movement exercise for improving the performance of distance runners as postulated by previous individuals (29,36). Whereas uphill running has largely been assumed to improve the running performance of distance runners, other high-intensity resistance-to-movement training tactics such as explosive and heavy strength training and plyometric training have been proven to have a positive impact on distance running performance (19,46,51,52,54). As identified previously, the key physiological determinants involved in distance running that explain more than 70% of the interindividual variances among well-trained runners include $\dot{V}O_2max$, the blood lactate threshold, and running economy (1,15). With no evidence having emerged to support the improvement of $\dot{V}O_2max$ or the blood lactate threshold, resistance-to-movement exercises such as explosive and heavy strength training and plyometric training appear instead to enhance running economy by improving neural input and muscle power factors. Supporting these previous findings, in the present investigation, neither $\dot{V}O_2max$ nor $V_{LT}$ significantly increased in $G_{Hill}$ in response to training and perhaps a similar improvement in either neural input or muscle power factors played a role in the significant improvement in $T_{max}$.

Further to the discussion of the impact of muscle power factors in distance runners, Paavolainen et al. (42,43), in 2 investigations, showed the importance of power output in distance runners and the benefit to incorporating resistance-to-movement training techniques to improve ground contact dynamics. Moreover, in describing muscle power factors and their impact on distance running performance, Noakes (40) suggested that the distance covered at a high velocity influences muscular adaptations and maximizes the number of powerful muscle contractions. As well, Nummela et al. (41) determined that a significant relationship existed between 5 km time and reduced ground contact time in a group of distance runners, leading the authors to conclude that distance running ability can be impacted by neural input and neuromuscular capacity– 2 factors linked directly to the ability to generate faster top running speeds and influenced, ostensibly, by using at or near maximum intensities during training.

Although we did not directly quantify kinetically or physiologically, the effort involved in an uphill interval bout in the present investigation, running at 10% incline and 100% $V_{max}$ for 30 seconds clearly represented a degree of high-intensity training (by $G_{Hill}$)–arguably more sport specific than other high-intensity resistance-to-movement exercises–indicative of the high-velocity explosive movements associated with at or near maximum effort running. For example, throughout the course of the 6-week intervention, the investigator observed in each participant an unlikely ability to run much beyond the required 30-second bout, if at all. This observation, along with the revelation that $G_{Hill}$ participants routinely exercised approximately half the time during interval sessions compared with $G_{Flat}$ (approximately 10–14 vs. approximately 18–27 minutes per week, respectively), and yet still significantly improved $T_{max}$, suggests that uphill training–perhaps by impacting muscle power factors in ways similar to other high-intensity resistance-to-movement exercises–can positively impact endurance performance in already well-trained distance runners.

In the present study, the fact that $T_{max}$ significantly improved in response to fixed 30-second bouts represents a somewhat novel finding because few of the investigations into this sort of supramaximal/high-intensity training have examined runners. In one such study, a 4-week intervention observing a group of moderately trained distance runners who performed 3 high-intensity interval training sessions per week, Iaia et al. (26) determined that 8–12 bouts of 30-second duration at approximately 22.4 km per hour (a speed corresponding to approximately 93% of that achieved during an "all-out" 30-second bout pretest) during each session led to lower energy expenditure during submaximal running. Also of interest, during the 4-week training intervention, total training volume was reduced by two-thirds compared with pretraining, and yet levels of muscle oxidative enzymes, capillarization, $\dot{V}O_2max$, and 10 km running time were maintained. These outcomes suggest a profound impact associated with performing high-intensity intervals that may influence decisions regarding training program design, including the volume and intensity of training and tapering considerations in leading up to competition.

Mohr et al. (38) conducted an 8-week study involving high-intensity interval training and had participants complete more than 32 total training sessions. Using moderately trained male athletes, a significant change in a time-to-exhaustion test occurred after performing eight 30-second bouts at an intensity corresponding to approximately 130% $\dot{V}O_2max$ during each training session. In contrast, time to exhaustion did not improve in those athletes carrying out training sessions using fifteen 6 second runs while running at an intensity equal to approximately 95% of maximum speed. Macpherson et al. (34) carried out a 6-week investigation of moderately trained individuals undertaking either sprint interval training or endurance training. Performing 4–6 bouts of all-out 30 second runs during each of 3 weekly training sessions, those in the sprint interval training group significantly improved 2 km run time, body composition, and both central and peripheral oxygen transport and uptake dynamics. In comparison, while the endurance training group also significantly improved in the same measurements, they did so while maintaining an approximately 200% greater weekly time commitment to exercise compared with the sprint interval group, suggesting that perhaps a lower volume higher intensity approach to training has merit for improving performance compared with a more traditional higher volume lower intensity approach to training (34).

In nonrunning investigations using high-intensity interval training, MacDougall et al. (33) examined performance and enzymatic changes in a group of cyclists performing 3 high-intensity interval training sessions per week for 7 weeks and found that completing 4–10 all-out 30-second bouts per session resulted in significant improvements in both glycolytic and muscle oxidative enzyme activity, maximum short-term power output, and $\dot{V}O_2max$. Furthermore, Laursen et al. (32) investigated the effects of 4 weeks of performing 12 all-out 30-second bouts during 2 sessions per week in well-trained cyclists and reported significant improvements in 40 km time trial performance, ventilatory threshold, and maximum heart rate (during the 40-km time trial). Based on these observations, the authors concluded that 40 km time trial improvement could be explained in part by increased glycogenolytic flux and increased muscle buffer capacity associated with sprint interval training (32). In the present investigation, although we did not assess muscle buffer capacity, perhaps a similar phenomenon may have played a role in the significant improvement of $T_{max}$ in $G_{Hill}$ in response to the all-out 30-second bouts associated with uphill running.

In the first of several cycling studies, Burgomaster et al. (11) reported just 6 sessions for 2 weeks, each including 4–7 all-out 30-second sprints on a cycle ergometer (and totaling approximately 15 minutes of intense exercise for the 2 weeks), which resulted in nearly doubling the time to exhaustion (approximately 26–51 minutes) during a ride at 80% of $\dot{V}O_2max$. A second study using the same training protocol showed a significant improvement in the time required to complete a 250-kJ cycling time trial (9), and in a third project, despite a nearly 90% difference in total training volume, a group performing sprint interval training compared with "traditional" endurance training achieved similar adaptations in skeletal muscle carbohydrate and lipid metabolism and selected markers of metabolic control (10). Based on the findings of the present investigation, in addition to those listed above, it appears using training prescriptors of near maximum intensity combined with 30-second interval bouts has merit as a training tactic that may be useful in shaping decisions for training program design.

Regarding $G_{Flat}$, our finding that $T_{max}$ significantly improved in response to high-intensity interval training using 100% $V_{max}$ and 60% $T_{max}$ as training prescriptors matches the conclusions of previous investigators and further substantiates this training approach when seeking to improve running performance in well-trained runners. For example, Smith et al. (50), researching the effects of 2 weekly high-intensity interval training sessions for 4 weeks in a group of well-trained triathletes and middle distance runners, reported that a protocol incorporating 100% $V_{max}$ and bout durations ranging 60–75% $T_{max}$ yielded significant improvements in $V_{max}$, $T_{max}$, and 3 km time trial performance. In a later study conducted by the same author and using a similar 4-week protocol, a group of well-trained middle and long distance runners and triathletes using 100% $V_{max}$ and 60% $T_{max}$ responded with significant improvements in $T_{max}$ and 3 km running time.

Denadai et al. (14) also used 60% $T_{max}$ interval lengths to examine 2 groups of well-trained distance runners performing 2 high-intensity interval training sessions per week for 4 weeks. With one group undertaking 95% $V_{max}$ and 60% $T_{max}$ training and the other using 100% $V_{max}$ and 60% $T_{max}$, the authors found that despite not improving $\dot{V}O_2max$, both groups produced significant improvements in $V_{max}$, 1,500 m, and 5 km time trial performance (14). In a study that used a training protocol very similar to the current investigation, Esfarjani and Laursen (17) examined 2 types of high-intensity interval training programs in moderately trained runners.

Training 4 days per week–2 high-intensity interval days and 2 continuous running sessions–one group followed the same 100% $V_{max}$ and 60% $T_{max}$ protocol used in the present investigation, whereas the other group completed 8–12 bouts of 30-second duration at 130% $V_{max}$. Both groups significantly improved $\dot{V}O_2$max, $V_{max}$, $T_{max}$, and 3 km running performance, with $T_{max}$ improving by 35 and 32 seconds in the 60% $T_{max}$ and 30 second high-intensity interval groups, respectively. In comparison, in the present investigation, $T_{max}$ improved by 68 and 138 seconds in $G_{Hill}$ and $G_{Flat}$, respectively.

Explaining the physiological rationale for using 100% $V_{max}$ and 60% $T_{max}$ as training prescriptors to improve distance running performance has much support in the literature when attempting to maximize both the time spent at $\dot{V}O_2$max and the total amount of work completed at a high intensity. Previous research has examined $V_{max}$ and shown that this running intensity enables individuals to remain at $\dot{V}O_2$max for longer durations during intermittent running compared with continuous running performed at intense but submaximal speeds (4,7). First introduced by Daniels et al. (13) in the late 1970s, the concept of $V_{max}$ combines $\dot{V}O_2$max and running economy into a single factor and explains differences in individual performances not accounted for by those factors alone . Others confirmed that $V_{max}$ correlates strongly with the velocity capable of being sustained by elite runners in distances up to 3 km (15,30) and that because it represents the minimum velocity needed to elicit $\dot{V}O_2$max, it should depict the ideal training intensity for events ranging from 1,500 m to marathon (6). From a practical standpoint, developing methods to individually and accurately assess $V_{max}$ and $T_{max}$ in the field, in the absence of sophisticated laboratory equipment, seems a prudent pursuit, given their potential impact on program design.

In using $T_{max}$ to prescribe individually based interval bouts for distance runners, earlier findings indicate that bouts lasting 60% $T_{max}$ result in the greatest time spent at $\dot{V}O_2$max. Reporting on the cardiopulmonary dynamics associated with a run-to-exhaustion test performed at 100% $V_{max}$, Hill and Rowell (22) investigated 13 moderately trained female track athletes and determined that interval durations less than 60% $T_{max}$ did not allow enough time for most individuals to reach $\dot{V}O_2$max. A second study by Hill et al. (23)–this time using 6 well-trained male runners–provided similar results, in that none of the runners in the study, who also used 100% $V_{max}$ as their training intensity, achieved $\dot{V}O_2$max within the first 60% of a $T_{max}$ test. In contrast to the findings of Hill et al. on bout duration, Billat et al. (5) found that 1 interval session per week over 4 weeks in a group of well-trained runners using 100% $V_{max}$ and bout durations equal to 50% $T_{max}$ resulted in significant improvements in $V_{max}$. Smith et al. (49), reporting on interval bouts greater than 60% $T_{max}$, investigated a group of runners using 100% $V_{max}$ and 70% $T_{max}$ and found that even though improvements occurred in a variety of indices in response to the training, none of the improvements were significant. On closer review, the authors concluded that bout durations of this length proved too difficult–resulting in less total time spent running during each interval session compared with a group using 60% $T_{max}$–even for a group of well-trained endurance athletes. As borne out by the improvement of $T_{max}$ in $G_{Flat}$, the present investigation further validates the approach of using 100% $V_{max}$ and 60% $T_{max}$ as training prescriptors for improving the performance of already well-trained distance runners.

Other studies investigating various combinations of training volume and intensity include a 10-week intervention by Enoksen et al. (16) in which all well-trained participants ran 6 days per week. Despite a 29% reduction in total training volume (50 vs. 70 km per week), only the low-volume high-intensity participants experienced marked improvements in $V_{max}$, $V_{LT}$, and anaerobic capacity. Helgerud et al. (20) examined a variety of training intensities (based on HRmax) in moderately trained athletes who completed 3 sessions per week for 8 weeks. Of note, of the 4 groups, only the 2 that incorporated training intensities $\geq$ 90% HRmax significantly improved $\dot{V}O_2$max. In these groups, participants completed intervals of either 47 $\times$ 15 seconds (followed by 15 seconds of active recovery at 70% HRmax) or 4 $\times$ 4 minutes (with a 3-minute active recovery at 70% HRmax). In contrast, neither a group undertaking 45 minutes of long slow distance running (at 70% HRmax) nor a group completing approximately 24 minutes of continuous lactate threshold running (at 85% HRmax) experienced improvements in $\dot{V}O_2$max.

In light of the reporting in well-trained distance runners that showcases the merits of a variety of high-intensity interval training tactics and the pitfalls of a training program relying primarily on submaximal training, it bears repeating that in the present investigation, $G_{Con}$ participants, despite an average weekly time commitment to exercise that was more than 2 times greater than either $G_{Hill}$ or $G_{Flat}$ ($G_{Hill}$ = approximately 110–112 minutes per week; $G_{Flat}$ = approximately 113–122 minutes per week; $G_{Con}$ = approximately 238–286 minutes per week), did not significantly improve in any of the measured indices. A number of previous authors have suggested that in well-trained distance runners seeking to improve performance, the inclusion of high-intensity interval training must occur (1,2,25,35). Of note, in the present investigation, the investigator asked $G_{Con}$ participants to rate their training workouts on a scale of "Easy," "Moderate," or "Hard" and on only a few occasions did any $G_{Con}$ participants rate their training sessions as "Hard." This observation appears to support the conclusion of previous investigators that in already well-trained distance runners, a training program designed predominantly around low-intensity high-volume training without the inclusion of regularly scheduled high-intensity or interval training does not provide an adequate metabolic stimulus for improving performance.

In conclusion, both uphill and level-grade high-intensity interval training can improve, in already well-trained distance runners, the duration for a running bout completed at the velocity associated at $\dot{V}O_2max$. However, of the 2 approaches, the more traditional type of interval training–that performed at a level-grade and using a longer interval bout equal to 60% $T_{max}$–produced greater gains in a time-to-exhaustion test. Furthermore, this study begins to shed light on the efficacy of hill training, and future research should include examining a similar protocol with different running intensities, treadmill grades, and interval lengths. Also, investigating a variety of training protocols that combine both uphill and level-grade interval training seems warranted as this may replicate a more real-life training approach.

## Practical Applications

The coaches, runners, and industry pundits associated with distance running have long-touted the benefits of uphill training as part of total training approach, despite there being very little published research to support its physiological efficacy or any consensus as to the optimal training intensity, bout duration, and hill grade to use with this training tactic. Based on the outcomes of the present investigation, uphill running on a 10% grade at 100% $V_{max}$ with repeated 30-second bouts certainly appears to have merit as a training tactic. Not only does uphill training appear to significantly impact the metabolic processes associated with distance running but also these effects appear to occur in response to a relatively modest investment in total exercise time during an interval training workout. Therefore, performed as part of a comprehensive running plan or an occasional workout, uphill running represents a very efficient and economical use of time. One should keep in mind, however, that as the principle of specificity represents one of the major tenets of exercise science and sports training–and $G_{Flat}$ improved significantly more so than $G_{Hill}$ in $T_{max}$–uphill training on its own may not be the most beneficial mode of training if seeking to perform well on a predominantly flat-based running course. Therefore, the present investigation supports our initial hypothesis and the traditional view that level-grade interval training, using individually determined training intensities and bout durations, appears more effective than uphill interval training at improving distance running performance and remains a cogent and efficacious training approach.

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