The Effects of Incline and Level-Grade High-Intensity Interval Treadmill Training on Running Economy and Muscle Power in Well-Trained Distance Runners

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Abstract

Ferley, DD, Osborn, RW, and Vukovich, MD. The effects of incline and level-grade high-intensity interval treadmill training on running economy and muscle power in well-trained distance runners. *J Strength Cond Res* 28(5): 1298–1309, 2014—Despite a paucity of evidence, uphill running has been touted as a sport-specific resistance-to-movement training tactic capable of enhancing metabolic, muscular, and neuromuscular processes in distance runners in ways similar to previously established resistance-to-movement training methods, such as heavy and/or explosive strength training and plyometric training. Therefore, the purpose of this investigation included documenting the effects of incline and level-grade interval treadmill training on indices of running economy (RE) (i.e., oxygen consumption [$\dot{V}O_2$] and blood lactate [BLa] responses of submaximal running) and muscle power. 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 $\dot{V}O_2$max, 60.9 ± 8.5 ml·min^{-1}·kg^{-1}) received assignment to an uphill (G_{Hill} = 12), level-grade (G_{Flat} = 12), or control (G_{Con} = 8) group. G_{Hill} and G_{Flat} completed 12 interval and 12 continuous run sessions over 6 weeks, whereas G_{Con} maintained their normal training. Dependent variables measured before and after training were $\dot{V}O_2$ and BLa at 2 separate velocities associated with lactate threshold (V_{LT}) ($\dot{V}O_2$-60% and $\dot{V}O_2$-80%; and BLa-60% and BLa-80%, respectively); percentage of $\dot{V}O_2$max at lactate threshold (%$\dot{V}O_2$max at V_{LT}); muscle power as assessed through a horizontal 5-jump test ($5J_{max}$); and isokinetic knee extension and flexion at 3 angular velocities (90, 180, and 300°·s^{-1}). Statistical significance was set to $p \le 0.05$. All groups significantly improved $5J_{max}$, $\dot{V}O_2$-60%, $\dot{V}O_2$-80%, BLa-60%, and BLa-80%. Additionally, G_{Hill} and G_{Flat} significantly improved %$\dot{V}O_2$max at V_{LT}. Other indices of RE and muscle power did not improve. We conclude incline treadmill training effective for improving the components of RE, but insufficient as a resistance-to-movement exercise for enhancing muscle power output.

Key Words uphill training, sprint interval training, muscle power factors

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28(5)/1298–1309

Journal of Strength and Conditioning Research

Introduction

Over the years, a number of training tactics have been used to enhance the performance of already well-trained distance runners. For example, variations of either low-intensity, high-volume run training or high-intensity, low-volume run training have been shown to enhance the 3 primary determinants of distance running, namely maximum oxygen consumption ($\dot{V}O_2$max), the running velocity associated with the lactate threshold (V_{LT}), and running economy (RE) (2,32,42). As well, recent evidence suggests that incorporating resistance-to-movement training methods into the training programs of distance runners, such as heavy strength training, explosive strength training, and plyometric training can positively impact running performance in general and RE in particular (reported as oxygen consumption [$\dot{V}O_2$] at a submaximal speed) even in the absence of concomitant improvements in either $\dot{V}O_2$max or V_{LT} (38,43,48,49).

Resistance-to-movement training methods, such as heavy strength training, explosive strength training, and plyometric training involve using a percentage of 1-repetition maximum (1RM) or body weight and have been shown to enhance distance running performance by improving the muscular and the neuromuscular characteristics–often referred to in the literature as muscle power factors–of the lower body musculature during the landing and take-off phase of running. Investigations highlighting the benefits of heavy strength training and distance running performance suggest that performing exercises such as squats and leg presses while using intensities >85% 1RM can induce muscular adaptations resulting in shifts within muscle fiber type groups, and increases in anaerobic enzyme activity, force output, and intramuscular glycogen stores (42). Conversely, both explosive strength training and plyometric training involve high-velocity muscle contractions targeting the stretch-shortening cycle (SSC) and have been shown to enhance motor unit recruitment, synchronization, and rate of force development (37) when using intensities ranging 30–60% 1RM (1) and body weight, respectively, while performing exercises such as jump squats, bounding, and single- and double-leg box jumps.

Uphill running has long been used by distance runners as a key training component to a comprehensive training approach in the assumption that it represents a high-velocity, sport-specific resistance-to-movement training method capable of enhancing distance running performance via improvements in muscle power factors (32). However, this form of training, although widely touted by coaches, athletes and industry lay-journals as a means to increase running speed–and ultimately race performance–remains anecdotal, uninvestigated, and largely unsubstantiated from a physiological perspective, without proven recommendations for running intensity, bout duration, bout number, or hill grade. Instead, the vast majority of peer-reviewed investigations showcasing the effects of over-ground uphill running or incline treadmill running come from biomechanical investigations highlighting the electromyographical activity (EMG), kinematic, and kinetic response of these forms of training. Based on these biomechanical investigations, it seems over-ground uphill and incline treadmill running compared with level-grade running of the same conditions results in increased muscle activation and work performed at the ankle, knee, and hip–with only slight kinematic differences–and therefore represents a functional, sport-specific mode of training (18,45,50).

Since many coaches and distance runners incorporate uphill training as part of a comprehensive distance running training routine despite physiological efficacy, we sought to conduct an investigation comparing high-intensity incline treadmill training with a traditional level-grade high-intensity interval training approach on a treadmill. Therefore, the purpose of this study included documenting, in well-trained athletes, a variety of metabolic, muscular, and neuromuscular outcomes associated with high-intensity interval training performed during incline running on a treadmill at a 10% grade compared with level-grade high-intensity interval treadmill running. We chose to use treadmill training for this investigation as previous research has suggested adequately powered and noncompliant treadmills can replicate the EMG, kinematic, and kinetic patterns associated with over-ground running conditions (25,27,39,44) while also allowing for greater training precision and control over environmental factors. In pursuing this investigation, we incorporated previously reported training prescriptors shown to be effective for enhancing running performance. In particular, other investigators have reported that when seeking to improve the performance of well-trained distance runners, training velocities that elicit ≥90% $\dot{V}O_2$max (33,41), and bout durations that allow for the maximum amount of work at a high intensity (4), must be used. Therefore, we used the running velocity associated with $\dot{V}O_2$max, termed V_{max}, as the standard training intensity for both the experimental groups, while using bout durations equal to a fixed 30 seconds, or individually determined 60% of the time for which V_{max} can be maintained, termed 60%T_{max}. Previous research into multiweek high-intensity over-ground and treadmill-based interval training programs has revealed that using these training prescriptors has led to significant improvements in specific physiological indices associated with distance running and endurance performance (13,14,30,46,47).

We hypothesized that high-intensity interval training on a treadmill at both a 10% and level-grade would result in significantly improved RE and muscle power output compared with a group of controls, but that gains from incline treadmill training would be more pronounced. In reporting on the outcome measures, we used previously described methods to assess RE and muscle power output in distance runners including submaximal measurements of $\dot{V}O_2$ and blood lactate (BLa) (10), maximal horizontal jump performance (9,38) and both right- and left-side isokinetic knee extension and flexion torque output (3,16,26,51).

Methods

Experimental Approach to the Problem

The experimental design of this study was a parallel, 3-group, longitudinal (pretraining and post-training) approach with participants receiving assignment to an incline (G_{Hill}), level-grade (G_{Flat}), or control (G_{Con}) group. Training group represented the independent variable, whereas dependent variables consisted of a variety of physiological and biomechanical indices including: (a) $\dot{V}O_2$ at 60, 80, and 100% V_{LT}; (b) the BLa response at 60 and 80% of V_{LT}; (c) percent of $\dot{V}O_2$max achieved at V_{LT}; (d) maximum distance covered in a horizontal 5-jump test; and (e) average peak torque output during right- and left-side isokinetic knee extension and flexion testing at 90, 180, and $300° \cdot s^{-1}$, respectively.

Subjects

In addition to contacting members of a local running club, we also recruited potential participants through social media and word-of-mouth. Thirty-two well-trained participants (14 men and 18 women) who consistently engaged in weekly running sessions 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 and training procedures. Inclusion criteria for male and female participants required having competed a 5-km run in under 21:00 and 24:00, respectively, within the previous 12 months, having avoided high-intensity interval training in the previous

3 months, and being 18-35 years of age. We 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

During an initial visit to determine if the participant met the investigation's inclusion criteria, we asked each individual his or her willingness to be randomly assigned to 1 of 3 groups. Those unwilling to participate in either of the 2 experimental groups' training methods received assignment to a control group ($G_{Con} = 8$) and maintained their normal training routine. Those willing to participate in either of the 2 experimental groups' training tactics were matched according to the $\dot{V}O_2$max, and then randomly assigned to an incline interval training group ($G_{Hill} = 12$) or level-grade interval training group ($G_{Flat} = 12$). The study took place from January to August, 2011 and consisted of (a) familiarization training, (b) pretraining testing, (c) a 6-week training intervention, and (d) post-training testing.

Familiarization Testing. In the week before the start of the testing and training program, participants reported to the training center on 2 separate occasions to become familiarized with a warm-up routine, $\dot{V}O_2$max test, 5-jump test ($5J_{max}$) for distance, and isokinetic dynamometer (Cybex 6000; Lumex, Inc., Ronkonkoma, NY, USA) knee extension and flexion test. On the first visit, each participant performed a 10-minute run on a treadmill at a self-selected speed, followed by an additional 10–15 minutes dynamic warm-up routine. Following a 5-minute rest, each participant then completed a familiarization $\dot{V}O_2$max test. At the completion of the $\dot{V}O_2$max familiarization test, the investigator explained the concept of V_{LT} and RE and the processes involved in collecting these data. During the second visit, each participant completed 6–8 trials of a 5 J_{max}, followed by a single trial of isokinetic knee extension and flexion testing at each of 3 separate angular velocities. The participants completed the same warm-up routine before every testing and training session throughout the 6-week program. For all performance testing, participants were instructed 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 post-training session. Additionally, attempts were made to ensure all participants completed pretesting and post-testing procedures at approximately the same time of day. All testing days were separated by 2–3 days.

Performance Testing. Within 7 days of completing the $\dot{V}O_2$max 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 $\dot{V}O_2$max, $V_{LT,}$ the $\dot{V}O_2$ corresponding to V_{LT} ($\dot{V}O_2$ at V_{LT}), and the percent $\dot{V}O_2$max occurring at V_{LT} (%$\dot{V}O_2$max at V_{LT}). Day 2 testing involved assessments of $5J_{max}$, average peak torque output during isokinetic knee extension and flexion at each of 3 separate angular velocities, and RE at 60 and 80% V_{LT} ($\dot{V}O_2$-60% and $\dot{V}O_2$-80%), respectively. Additionally, the investigator also collected BLa samples at both 60 and 80% V_{LT} (BLa-60% and BLa-80%), respectively.

The $\dot{V}O_2$max data were obtained using a breath-by-breath gas analyzing system (Physio-Dyne MAX-II; AEI Technologies, Inc., Bastrop, TX, USA), which collects expired gases in a mixing chamber, measures them continuously, and reports on averaged gas values in 15-second intervals. Before each test, the investigator calibrated the metabolic cart with gases of a known composition. The $\dot{V}O_2$max protocol consisted of having the participants complete 2-minute stages on a treadmill (Super Treadmill; Standard Industries, Fargo, ND, USA) set at a 1% grade (4). 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 a fingertip blood sample was collected and analyzed by using a 2.0- × 1.5-mm single-use contact-activated lancet (BD Microtainer; Becton, Dickinson and Co., Franklin Lakes, NJ, USA) and portable lactate analyzer (Lactate Plus; Nova Biomedical, Waltham, MA, USA). 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 successive stage, the treadmill speed was increased by $0.8\ km \cdot hr^{-1}$. The investigator used the following criteria to determine the participant's $\dot{V}O_2$max: (a) a respiratory exchange ratio >1.10, (b) an ending heart rate within ± $10\ b \cdot min^{-1}$ of age-predicted heart rate maximum (220-age), (c) no further increase in oxygen consumption despite an increased work rate, and (d) volitional exhaustion. Regarding BLa measurements and determining V_{LT}, the participant's V_{LT} was defined as that speed which elicited a $1\ mmol \cdot L^{-1}$ rise above baseline (10). (It should be noted that during the $\dot{V}O_2$max test, the investigator also determined each participant's V_{max}.)

Day 2 performance testing included, in the following order, $5J_{max}$, isokinetic knee extension and flexion, and RE. After performing the same warm-up routine, each participant completed 3 trials of a $5J_{max}$. The $5J_{max}$ took place on a portable runway (Plyorobic Runway; Ecore, Inc., Lancaster, PA, USA) and began with each participant assuming a starting position in which he or she placed his or her feet side-by-side, approximately shoulder width apart, at a starting line highlighted on the floor; thereafter, the participant jumped and landed on the foot of his or her preference. Following this first landing, without pause, the participant then jumped forward, as far as possible, onto the alternate foot 4 more times, before

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 wk	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

*G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†High-intensity training conditions: G_{Hill}: 100%V_{max}, 10% treadmill grade, 30-second work bout; G_{Flat}: 100%V_{max}, 1% treadmill grade, 60% T_{max}.
‡Continuous running conditions: G_{Hill} and G_{Flat}: 75%V_{max}, 1% treadmill grade, 45–60 minutes.

landing on both feet. The distance from the starting line to the front of the participant's nearest foot was measured. Each participant completed 3 trials, and the investigator used the average of the 3 trails for statistical purposes.

After a 10-minute rest, each participant completed right- than left-side isokinetic knee extension and flexion testing at 90, 180 and $300° \cdot s^{-1}$, respectively. The investigator determined seat, mechanical axis, and shin pad length settings during familiarization testing, and these same settings were used during all pretraining and post-training testing. In brief, each participant's positioning consisted of sitting upright on the testing table of the isokinetic dynamometer with stabilization straps across the chest and distal third of the thigh. The testing table on which the participant sat was adjusted to achieve a 90° angle between the torso and the thigh. Regarding the axis of movement, the investigator adjusted the participant's position to align the knee joint axis of rotation with the mechanical axis of the dynamometer. Finally, a shin pad with stabilization strap was placed on the anterior tibia just superior to the medial malleolus, and the investigator anchored 2 mechanical stoppers to allow 85 degrees of movement from 5 to 90° of knee flexion. In the order 90, 180, and $300 \cdot s^{-1}$, each test consisted of 5 practice repetitions at the respective angular velocity, followed by a 1-minute rest, and then 5 maximal efforts. At the end of the 5 maximal efforts, another 1-minute rest occurred before the participant repeated the same process for the next 2 angular velocities. Each participant received instructions to use a concentric muscle contraction to first extend the knee from 90° to 5° flexion against the shin pad of the dynamometer, and then flex the knee from 5 to 90° using a concentric contraction in returning to the starting position. Throughout the trials, each participant received verbal encouragement to produce maximal efforts during the 5 repetitions of the actual test phase.

After a 15-minute rest, each participant performed a test of RE at both 60% V_{LT} and 80% V_{LT}, respectively. The assessment of RE involved using the same metabolic cart and calibration procedures as described above. The RE protocol consisted of running for 210 seconds at 60% V_{LT}, followed by a 30-second pause during which time a fingertip BLa sample was collected and analyzed, and finished with an additional 210 seconds of running at 80% V_{LT} and finger tip BLa sample collection and analysis. As RE has been reported to reflect the $\dot{V}O_2$ associated with submaximal running speeds, the $\dot{V}O_2$ values during the last minute of each stage were averaged. (It should be noted that after the completion of the test of RE, and following a 10-minute rest, each participant completed a run-to-exhaustion test.)

TABLE 2. Pretraining vs. post-training values for $5J_{max}$.*†

	G_{Hill} (n = 12)	G_{Flat} (n = 12)	G_{Con} (n = 8)
$5J_{max}$ (m)			
Pre	10.85 ± 1.23	10.62 ± 1.42	10.80 ± 1.19
Post	11.07 ± 1.23‡	10.96 ± 1.46‡	10.89 ± 1.16‡
% Δ	2.0 ± 2.2	3.2 ± 3.3	0.8 ± 1.5

*$5J_{max}$ = 5-jump test; G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†Data are means (±*SD*) for maximal 5-jump horizontal test.
‡Significant time effect (pretraining to post-training) for all groups ($p \leq 0.05$).

Table 3. Pretraining and post-training isokinetic values for right- and left-side quadriceps.*†

Values represent the average of 5 maximum repetitions (N·m)	Right $90°·s^{-1}$	Left $90°·s^{-1}$	Right $180°·s^{-1}$	Left $180°·s^{-1}$	Right $300°·s^{-1}$	Left $300°·s^{-1}$
G_{Hill} ($n = 12$)						
Pre	161 ± 44	157 ± 47	122 ± 39	125 ± 38	90 ± 36	87 ± 32
Post	161 ± 45	154 ± 47	125 ± 40‡	126 ± 38	94 ± 37‡	92 ± 34‡
% Δ	0.0 ± 7.9	−1.9 ± 10.4	2.5 ± 6.2	0.8 ± 6.6	4.4 ± 7.8	5.7 ± 7.1
G_{Flat} ($n = 12$)						
Pre	148 ± 49	145 ± 44	110 ± 31	107 ± 32	82 ± 25	78 ± 26
Post	154 ± 49	154 ± 49	115 ± 37‡	114 ± 37	86 ± 30‡	84 ± 27‡
% Δ	4.0 ± 5.4	6.2 ± 9.5	4.5 ± 8.0	6.5 ± 10.4	4.9 ± 9.1	7.7 ± 12.0
G_{Con} ($n = 8$)						
Pre	140 ± 26	137 ± 24	106 ± 24	109 ± 26	79 ± 18	80 ± 21
Post	140 ± 26	140 ± 21	108 ± 23‡	107 ± 21	79 ± 16‡	80 ± 16‡
% Δ	0.0 ± 10.8	2.2 ± 8.9	1.9 ± 8.7	−1.8 ± 9.4	0.0 ± 8.3	0.0 ± 11.2

*G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†Data are means (±*SD*) for right- and left-side isokinetic knee extension at 3 angular velocities: $90°·s^{-1}$, $180°·s^{-1}$, and $300°·s^{-1}$.
‡Significant time effect (pretraining to post-training) for all groups ($p \leq 0.05$).

For both the $\dot{V}O_2$max and the RE 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. Within 2–3 days of the last continuous run session (approximately 4–5 days after the last high-intensity interval run session), each participant repeated day 1 testing procedures. Following an additional 2–3 days rest (approximately 6–7 days after the last high-intensity interval session), each participant repeated day 2 testing procedures.

Training Protocol. Although before the start of this investigation, all participants regularly engaged in moderate-intensity exercise 3–4 times per week, none routinely performed high-intensity interval training in the 3 months preceding the

Table 4. Pretraining and post-training isokinetic values for right- and left-side hamstrings.*†

Values represent the average of 5 maximum repetitions (N·m)	Right $90°·s^{-1}$	Left $90°·s^{-1}$	Right $180°·s^{-1}$	Left $180°·s^{-1}$	Right $300°·s^{-1}$	Left $300°·s^{-1}$
G_{Hill} ($n = 12$)						
Pre	97 ± 29	101 ± 33	79 ± 24	82 ± 28	62 ± 24	61 ± 22
Post	95 ± 28‡	103 ± 33	80 ± 26‡§	84 ± 27‡§	64 ± 22‡§	64 ± 23
% Δ	−2.0 ± 9.6	1.9 ± 9.0	1.3 ± 5.8	2.4 ± 6.2‖	3.2 ± 17.4	4.9 ± 6.5
G_{Flat} ($n = 12$)						
Pre	93 ± 20	86 ± 24	70 ± 15	72 ± 19	54 ± 15	55 ± 16
Post	98 ± 23‡	93 ± 25	75 ± 16‡	77 ± 22‡	58 ± 18‡	57 ± 20
% Δ	5.4 ± 6.9	8.1 ± 9.8	7.1 ± 3.9	6.9 ± 13.0‖	7.4 ± 9.0	3.6 ± 12.6
G_{Con} ($n = 8$)						
Pre	91 ± 26	89 ± 23	74 ± 23	75 ± 23	55 ± 16	51 ± 10
Post	88 ± 20	87 ± 20	72 ± 17	70 ± 17	51 ± 12	48 ± 10
% Δ	−3.3 ± 8.8	−2.2 ± 9.8	−2.7 ± 8.6	−6.7 ± 8.4	−7.3 ± 11.3	−5.9 ± 14.2

*G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†Data are means (±*SD*) for right- and left-side isokinetic knee flexion at 3 angular velocities: 90, 180, and $300°·s^{-1}$. A level of significance of $p \leq 0.05$ was used for all tests.
‡Significantly greater than post G_{Con}.
§Significantly different than post G_{Flat}.
‖Significantly different from G_{Con}.

Table 5. Pretraining and post-training values for $\dot{V}O_2$ ($ml \cdot min^{-1}$) and BLa concentration ($mmol \cdot L^{-1}$) at 60 and 80% of V_{LT}.*†

	$\dot{V}O_2$-60%	$\dot{V}O_2$-80%	BLa-60%	BLa-80%
G_{Hill} ($n = 12$)				
Pre	2187 ± 508	2824 ± 644	3.0 ± 1.7	3.2 ± 1.6
Post	2004 ± 542‡	2582 ± 671‡	1.9 ± 0.6‡	2.3 ± 0.8‡
% Δ	8.4 ± 12.5	8.6 ± 11.4	36.7 ± 36.8	28.1 ± 38.0
G_{Flat} ($n = 12$)				
Pre	2210 ± 453	2887 ± 615	2.1 ± 0.9	3.0 ± 1.4
Post	2117 ± 381‡	2769 ± 487‡	1.7 ± 0.8‡	1.9 ± 0.8‡
% Δ	4.2 ± 6.6	4.1 ± 6.5	19.0 ± 30.6	36.7 ± 36.4
G_{Con} ($n = 8$)				
Pre	2090 ± 449	2752 ± 512	2.1 ± 0.7	2.5 ± 0.9
Post	1948 ± 315‡	2530 ± 384‡	1.7 ± 0.5‡	2.1 ± 1.1‡
% Δ	6.8 ± 8.1	8.1 ± 7.5	19.0 ± 49.8	16.0 ± 45.2

*BLa = blood lactate; V_{LT} = lactate threshold; G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†Data are means (±*SD*) for oxygen consumption at 60 and 80% of V_{LT}, $\dot{V}O_2$-60,% and $\dot{V}O_2$-80%, respectively; and BLa concentration at 60 and 80% of V_{LT}, BLa-60%, and BLa-80%, respectively.
‡Significant time effect (pretraining to post-training) for all groups ($p \leq 0.05$).

training intervention. During the training intervention, both G_{Hill} and G_{Flat} used the same maximum and submaximum training intensities while performing 2 high-intensity interval sessions and 2 continuous run sessions per week, respectively, in an alternating fashion. In particular, G_{Hill} high-intensity interval sessions involved completing 10–14 bouts for 30 seconds on a treadmill set to a 10% grade while running at 100% V_{max}. Alternatively, G_{Flat} completed 4–6 bouts for a duration equal to 60% T_{max} on a treadmill set to a 1% grade and 100% V_{max}. On the days of continuous run training, both G_{Hill} and G_{Flat} ran for 45–60 minutes on a treadmill set at 1% grade and 75% V_{max}. During high-intensity interval training, both G_{Hill} and G_{Flat} participants wore the same heart rate monitor to track heart rates during rest periods, which in this study was defined as the time it took heart rate to return to 65% of age-predicated maximum (65% HRmax). Additionally, G_{Hill} and G_{Flat} tracked heart rate during all continuous run sessions; and following all running sessions heart rate data were downloaded to a personal computer. Participants in G_{Con} continued their normal weekly training and activity programs ($4.9 \pm 0.07\ d \cdot wk^{-1}$ and $270.4 \pm 81.6\ min \cdot wk^{-1}$) away from the training facility. During the 6-week training intervention, G_{Con} completed daily training diaries describing the duration and intensity of their training (easy, moderate, and hard), which the investigator analyzed at the end of the intervention.

Table 6. Pretraining and post-training values for $\dot{V}O_2V_{LT}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) and $\%\dot{V}O_2maxV_{LT}$.*†

	$\dot{V}O_2$ at V_{LT}	$\%\dot{V}O_2$max at V_{LT}
G_{Hill} ($n = 9$)		
Pre	50.5 ± 8.0	87.0 ± 4.7
Post	51.1 ± 6.3	89.1 ± 5.6‡
% Δ	1.2 ± 6.5	2.4 ± 3.9
G_{Flat} ($n = 12$)		
Pre	51.7 ± 6.8	87.4 ± 4.4
Post	53.2 ± 6.3	89.3 ± 5.2‡
% Δ	2.9 ± 5.2	2.2 ± 3.7
G_{Con} ($n = 8$)		
Pre	52.0 ± 7.0	87.0 ± 4.7
Post	51.4 ± 5.9	87.5 ± 4.2
% Δ	−1.2 ± 7.7	0.6 ± 6.3

*V_{LT} = lactate threshold; G_{Hill} = uphill group; G_{Flat} = level-grade group; G_{Con} = control group.
†Data are means (±*SD*) for oxygen consumption at VLT, $\dot{V}O_2$ at VLT; and percent maximum oxygen consumption at VLT, $\%\dot{V}O_2$max at VLT.
‡Significant time effect (pretraining to post-training) for all groups ($p \leq 0.05$).

All testing and high-intensity interval treadmill training sessions involved use of the Super Treadmill, while all continuous run training sessions involved using additional treadmills (Precor 932i, Precor USA Inc., Woodinville, WA, USA). The Super Treadmill and Precor 932i treadmill have running belt areas measuring 183 × 51 cm and 142 × 56 cm, respectively. Additionally, the speed and elevation capacities of the Super Treadmill ranged 0–48 $km \cdot hr^{-1}$ and −10 to 40%, respectively, whereas the Precor 932i treadmill specifications ranged 0–19.3 $km \cdot hr^{-1}$ and 0–15%, respectively. Each week the investigator calibrated all treadmills for speed and incline. Additionally, when running on the Super Treadmill, participants gathered visual feedback on the running form by means of a 183 × 91-cm wall-mounted mirror in front of the Super Treadmill. On high-intensity interval training days, the investigator administered and monitored the training sessions and giving "spotting" assistance as a safety precaution as needed. The 6-week group-assigned training protocol appears in Table 1.

Statistical Analyses

For all data analysis, the investigator used the statistical analysis program JMP (v.8.0.2, SAS Institute). Descriptive statistics of each outcome variable, including means, *SD*s, and tests of normality were determined. All dependent variables were assessed for percent change and analyzed with a 1-way analysis of variance (ANOVA) to determine differences between the groups. A mixed-design repeated measures ANOVA (3 × 2) was used to test for the effect of training and training group on $5J_{max}$, average peak torque output during right- and left-side isokinetic knee extension and flexion, $\dot{V}O_2$-60%, $\dot{V}O_2$-80%, BLa-60%, BLa-80%, $\dot{V}O_2$ at V_{LT}, and %$\dot{V}O_2$max at V_{LT}. 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

$5J_{max}$

All of the groups experienced a significant improvement in $5J_{max}$ after 6 weeks of training. However, there was no significant group effect or group-by-time differences in response to the training. Table 2 highlights the $5J_{max}$ results.

Isokinetic Knee Extension and Flexion

Although significant time and group improvements occurred in several measurements of knee extension and knee flexion in both G_{Hill} and G_{Flat}, no uniform improvements occurred in any of the groups. Therefore, we do not feel confident stating that either G_{Hill} or G_{Flat} treadmill training led to improved strength as measured isokinetically. Tables 3 and 4 contain the training investigation's effect on average peak torque output of the right- and left-side knee extensors and flexors, respectively, at 90, 180, and $300° \cdot s^{-1}$.

$\dot{V}O_2$ Response and Blood Lactate Concentration at 60 and 80% of V_{LT}

All 3 groups experienced a significant time effect improvement in $\dot{V}O_2$ and BLa responses at the 2 tested submaximal running velocities after 6 weeks of training. However, there was no significant group effect or group by time differences in response to the training. Table 5 contains the training investigation's effect on $\dot{V}O_2$-60, $\dot{V}O_2$-80, BLa-60, and BLa-80%.

$\dot{V}O_2$ at V_{LT} and %$\dot{V}O_2$max at V_{LT}

Because of equipment malfunction, the investigator excluded the results of 3 G_{Hill} participants from statistical evaluation. After 6 weeks of training, none of the groups experienced significant improvements in $\dot{V}O_2$ at V_{LT}. Regarding the percentage of $\dot{V}O_2$max achieved while running at V_{LT}, after training, both G_{Hill} and G_{Flat} experienced a significant increase in %$\dot{V}O_2$max at V_{LT}. However, there was no significant group effect or group by time differences in response to the training. Table 6 highlights the training investigation's impact on $\dot{V}O_2$ at V_{LT} and %$\dot{V}O_2$max at V_{LT}.

Discussion

Uphill running represents a frequently used and often-prescribed training tactic in the development of competitive distance runners. In fact, previous research indicates this mode of training correlates strongly with overall cross-country team success at the NCAA Division I National Championship level (28). Moreover, uphill running has been suggested to be a high-velocity resistance-to-movement exercise capable of improving distance running performance in a manner similar to other high-velocity and/or high-intensity resistance-to-movement training (32). However, while previous research has substantiated the beneficial impact of heavy strength training, explosive strength training, and plyometric training on running performance–and in particular RE, and the muscular and neuromuscular indices associated with muscle power–to date, no evidence exists to show that uphill training enhances RE or muscle power output. Therefore, the purpose of this investigation sought to examine the effects of both incline and level-grade high-intensity interval treadmill training on the $\dot{V}O_2$ and BLa responses associated with submaximal running and report on the muscle power characteristics associated with maximum-intensity horizontal jumping and isokinetic testing.

In this investigation, the main findings show that high-intensity interval running performed on a treadmill at a 10% grade significantly improved specific indices of RE to the same extent as level-grade high-intensity interval treadmill training. Specifically, $\dot{V}O_2$ and BLa responses at both 60 and 80%V_{LT} significantly improved in all 3 groups, while only G_{Hill} and G_{Flat} experienced significant improvements in % $\dot{V}O_2$max at V_{LT}. In terms of indices of muscle power, all groups experienced significant increases in $5J_{max}$ after training, but no group improved significantly more so than another. Moreover, although significant improvements occurred in measures of isokinetic strength in both G_{Hill} and G_{Flat}, these improvements were nonuniform and did not reveal an obvious group effect. Therefore, based on the outcomes of this investigation, high-intensity interval treadmill training performed at a 10% grade does improve certain components of RE in well-trained runners, but it does not substitute for traditional resistance-to-movement training exercises previously shown to enhance muscle power factors. Moreover, our hypothesis that high-intensity interval training on a treadmill using a 10% grade would produce greater gains in measures of RE and muscle power output compared with performing either high-intensity interval training on a treadmill at level-grade or training on one's own was not met.

With the exception of the specific measures of RE, the findings relating to muscle power outcomes in this investigation are not in agreement with previous investigations showing that resistance-to-movement exercises, such as heavy strength training, explosive strength training, and plyometric training can lead to enhanced RE, muscle power, and running performance (34,35,38,43,49). Using a variety of training intensities based on a percentage of 1RM or body weight, these modes of resistance-to-movement training have led to significant increases in force output, motor unit recruitment, rate of force development, and synchronization

–collectively referred to as muscle power factors–that have been shown to impact the SSC associated with the landing and take-off phase of running (37,42). However, whereas resistance-to-movement training investigations have assessed the impact of heavy strength training, explosive strength training, and plyometric training on measures of running performance, in this investigation, we measured the opposite; that is, we assessed the impact of incline and level-grade high-intensity interval treadmill running on measures of RE and muscle power output, which may not represent the best means for determining, in particular, the muscular or neuromuscular effects associated with these approaches to training.

Similar to this investigation, other research efforts have failed to find a significant training effect on RE following a period of high-intensity interval training or resistance-to-movement training. An investigation into a group of well-trained middle distance runners, triathletes and 10-km runners revealed no significant improvements in RE following 4-weeks of high-intensity interval treadmill training using either 60 or 70% T_{max} bout durations despite improvements in 5-km time trial performance (46). Moreover, 10-weeks of periodized strength training using a variety of lower body exercises led to significant improvements in 1RM, but not $\dot{V}O_2$peak, RE, or 3-km time trial performance in a group of female distance runners (24); and 6 weeks of periodized strength training in a group of well-trained runners actually led to a worsening of RE (29).

In this study, the fact that neither RE nor muscle power displayed a significant group training effect in G_{Hill} or G_{Flat} represents a special point of interest given the fact that both the experimental groups, as reported previously, significantly improved in a run-to-exhaustion (T_{max}) while running at V_{max} (14). However, several explanations may exist to partially explain these phenomena. For instance, previous research indicates that well-trained, highly experienced runners already display greater RE than either good, untrained, or novice runners, and therefore, it may be more difficult to improve RE in well-trained, highly experienced runners (5,36). Based on their $\dot{V}O_2$max values, our participants represented a generally accepted definition of well-trained endurance runners (11,46). Furthermore, the authors acknowledge the effects of timing on post-testing and recognize the potential for type II errors in reporting our results; that is, had a longer rest period been applied before post-testing, perhaps: (a) significant improvements would have been observed in additional outcome measures, and/or (b) the significant improvements observed would have been greater. However, previous running investigations used a similar post-testing period and reported significant improvements in measures of RE and muscle power following a period of intense sprint interval or resistance-to-movement training (38,48,52). Specificity of training may have also influenced the outcome measures; that is, all RE outcome measures in this investigation were assessed while running at a level-grade, and perhaps additional incline-based assessments would have revealed performance improvements correlating to a more "real-life" running course consisting of both hilly and flat terrain.

An insufficiency of high-intensity training volume in this investigation may partially explain the lack of additional significant improvements in RE or muscle power within the groups or a significant group training effect. For example, G_{Hill} and G_{Flat} completed a relatively modest number of 12 total high-intensity training sessions over 6 weeks, with each high-intensity interval treadmill training session consisting of just 5–7 and 9–13 minutes of total running, respectively (14). However, both G_{Hill} and G_{Flat} training interventions in this investigation were based on previous investigations of both shorter and longer duration that incorporated similar training intensities, bout durations, bout number, and training sessions and which reported significant improvements in a variety of physiologically based indices including RE (13,30,46). For example, Esfarjani et al. (13) investigated 10 weeks of treadmill training and nearly identical G_{Hill} and G_{Flat} training prescriptors in moderately trained athletes performing either short-bout or long-bout level-grade high-intensity interval training, and reported that although both groups improved significantly in a variety of outcome measures, those completing longer-bout 60%T_{max} high-intensity training at 100%V_{max} improved to a significantly greater extent than those completing 30-second high-intensity interval training at 130%V_{max}. Comparatively, those completing short-bout and long-bout high-intensity interval training improved T_{max} by 99 and 117 seconds, respectively, whereas as we reported previously (14) G_{Hill} and G_{Flat} significantly improved T_{max} by 70- and 139-second, respectively. Esfarjani et al. (13) also reported that a group of controls completing 60 minutes of submaximal intensity treadmill running 4 times per week did not improve significantly in any outcome measure, including T_{max}. As we reported previously (14), 7 of 8 G_{Con} participants were in training to complete a half- or full-marathon and appeared to perform an abundance of submaximal training as they ranked nearly all of their training sessions as either "easy" or "moderate," which resulted in them training significantly more than G_{Hill} or G_{Flat} each week (269 minutes vs. 112 minutes and 118 minutes, respectively). However, in this investigation, G_{Con} significantly improved RE to the same extent as G_{Hill} and G_{Flat}, which may be explained by previous research reporting that even in already well-trained individuals a high-volume, low-intensity run training program may lead to significant improvement in indices of RE (12,19,37).

Other shorter research studies using training interventions similar to this investigation include Smith et al. (46,47), who had well-trained runners in 2 separate investigations perform twice-weekly high-intensity interval treadmill training for 4 weeks and reported that using 100%V_{max}, bout durations ranging 60–70%T_{max}, and bouts totaling 4–6 per session led to significant improvements in $\dot{V}O_2$max, V_{max}, T_{max}, and 3-km time trial performance in well-trained runners. One of the main conclusions derived by Smith et al. (46) was that bouts performed using $100\%V_{max}$ and $60\%T_{max}$ proved to be more effective than bouts performed using $100\%V_{max}$ and $70\% T_{max}$ because the latter resulted in excessive fatigue, fewer bouts completed than prescribed, and overall led to less work performed at a high-intensity each session compared with the $60\%T_{max}$ group. As such, while T_{max} significantly improved by 50 seconds in those completing $100\%V_{max}$ and $60\%T_{max}$ bouts, it did not improve significantly in those completing $100\%V_{max}$ and $70\%T_{max}$ bouts (46).

Many of the resistance-to-movement studies cited above incorporated multiexercise, periodized approaches with at least 3 days of training per week for more than 6 weeks (34,35,38,43,49). As a result, the overall volume of high-intensity training performed in the present investigation may simply have been insufficient or the study duration too short to induce the type of metabolic, muscular, or neuromuscular adaptations that have led to significant improvements in RE and muscle power as seen in other investigations. As well, we used the submaximal running speeds of 60 and 80% V_{LT} to assess RE as previous research has suggested that when evaluating RE, speeds that elicit $<85\%$ $\dot{V}O_2max$ should be used since faster speeds may induce anaerobic metabolism (42). However, it may be possible that different submaximal running speeds would produce different findings. For example, Saunders et al. (43) assessed RE in a group of well-trained distance runners at 3 separate submaximal speeds and found that only the fastest speed of 18 $km \cdot hr^{-1}$ resulted in significant improvements in RE, whereas the slower speeds of 14 and 16 $km \cdot hr^{-1}$ did not.

Of special interest, despite a significant difference in run time that resulted in G_{Hill} performing nearly 50% less total work than G_{Flat} (5–7 vs. 9–13 minutes, respectively) during each high-intensity interval session (14), G_{Hill} experienced a greater improvement in reduced $\dot{V}O_2$ and BLa production at each of 2 submaximal running velocities compared with G_{Flat}. These trends may indicate that incline treadmill training represents a practical, sport-specific mode of training effective for enhancing submaximal performance. The profound impact of low-volume, high-intensity interval training has been reported in both running and cycling studies in which all or a substantial amount of typical endurance training was replaced with relatively modest amounts of high-intensity interval training. For example, Iaia et al. (20) replaced all endurance training with sprint interval training in a group of endurance-trained individuals for 4 weeks and reported that 3 weekly sessions of 8–12 nearly "all-out" 30-second sprints not only maintained adaptations gained from a previous training cycle but actually improved RE. Burgomaster et al. (8) designed an investigation in which groups performed either sprint interval training or endurance training 3 or 5 days per week, respectively, for 6 weeks, and during which the sprint interval group purposely performed ~90% less total training than the endurance group. Despite the lower training volume and total time commitment each week, both groups experienced comparable adaptations in markers of skeletal muscle carbohydrate and lipid metabolism and metabolic control. Hence, in the present investigation, perhaps performing additional weekly sessions of high-intensity interval training, or extending the number of weeks of training would have resulted in a significant group training effect in the outcome measures.

A general lack in high-intensity training volume may also explain the statistically nonsignificant gains observed in $5J_{max}$ and right- and left-side Cybex isokinetic knee extension and flexion. As the adaptation to an imposed demand represents one of the fundamental tenets of exercise science, previous research has shown that training with an appropriate stimulus can result in gains in absolute strength and power output in as little as 2 to 3 weeks (15). Consequently, running on an inclined treadmill using our protocol's training prescriptors may simply have been too inadequate a stimulus for effecting muscular or neuromuscular adaptations. For instance, to maintain a constant center of mass on a treadmill with an elevated grade, the average resultant treadmill reaction force during the stance phase must roughly equal body weight to counter the effects of gravity (50); however, ground reaction forces produced during heavy strength training, explosive strength training, plyometric training, and high-intensity level-grade running often exceed body weight by a factor of 3 or more (21,23). Hence, a minimum ground reaction force threshold may exist below which no muscular or neuromuscular adaptations occur; and although numerous investigations have incorporated the use of running treadmills, the authors acknowledge this form of training represents a potential limitation compared with over-ground uphill running, which may reveal ground reaction forces similar to these other resistance-to-movement conditions. The alternative explanation may be that incline treadmill training does not improve strength or power as determined by the outcome measures used in this investigation. From an anecdotal perspective, an interesting observation was that within 3 weeks of completing their participation in this investigation, 3 G_{Hill} and 4 G_{Flat} participants competed in an annual area road race offering 5-km and 10-km distances, respectively, and recorded personal best performances, which may suggest that high-intensity incline and/or level-grade treadmill training, performed indoors during the winter months when high-quality outdoor training may be difficult to achieve in cold-weather climates, transfers to an over-ground training and/or racing setting.

Additionally, although isokinetic testing using angular velocities between 60 and $300° \cdot s^{-1}$ has been used previously to describe the characteristics of muscle power output in the knee extensors and flexors of distance runners (16,17,51), we have to acknowledge the limitation of using this single-joint testing modality for assessing the dynamic nature of running. Roberts and Belliveau (40), for example, determined that virtually all increases in work output associated with running up increasingly steeper grades (on a specially built ramp with force plate) at 3.0–3.5 $m \cdot s^{-1}$ resulted from increased net work done at the hip. Similarly, Swanson and Caldwell (50) determined that incline treadmill running at 4.46 $m \cdot s^{-1}$ and 30% grade compared with running on a level-grade at the same stride frequency (7.61 $m \cdot s^{-1}$) led to a significant increase in muscular loading in both the hip flexors and extensors throughout the swing phase of sprinting. Perhaps most applicably, previous research has shown angular velocities at the knee during fast running can exceed $1000° \cdot s^{-1}$ (22,50), and therefore we must acknowledge that even at the tested angular velocity of $300° \cdot s^{-1}$, the force-velocity characteristics involved with high-intensity running may not be adequately assessed with isokinetic dynamometry.

The learning effect associated with testing may have had an impact on the outcome measures muscle power output and may explain, in particular, the comparable improvements of all 3 groups in $5J_{max}$. Specifically, although each participant in this investigation completed a familiarization trial of $5J_{max}$, previous research has suggested that in tests that are novel at least 2 or 3 familiarization trials may be needed to negate a motor learning effect and highlight a true physiological change (6,7). As a result, in the absence of a significant group effect, it may be that all 3 groups experienced significant improvements in $5J_{max}$ due solely to a learning effect. Alternatively, G_{Hill} and G_{Flat} training interventions may have led to true physiological changes in $5J_{max}$, whereas incomplete reporting of training sessions by G_{Con} may have confounded these results because despite recording both the duration and intensity of their workouts (easy, moderate, and hard), they did not report on the terrain on which they ran. Therefore, G_{Con} participants may have run workouts on a hilly terrain to the extent it impacted their muscle power output, leading to significant improvements $5J_{max}$. Finally, the authors acknowledge the automatic assignment into G_{Con} of those participants unwilling to participate in either experimental groups' training protocol represents a limitation which may have impacted the results of the outcome measures; however, as reported previously, there were no significant differences in $\dot{V}O_2max$ between the 3 groups, and it seems all participants had a similar initial training status (14).

In conclusion, 6 weeks of incline and level-grade high-intensity interval treadmill training led to statistically significant improvements in measures of $\dot{V}O_2$ and BLa at both 60 and 80%V_{LT}, as well %$\dot{V}O_2max$ at V_{LT}, in G_{Flat} and G_{Hill}. Additionally, statistically significant improvements also occurred in $5J_{max}$ and several indices of single-side isokinetic knee extension and flexion in G_{Hill} and G_{Flat}. Since a major intent of this investigation focused on the efficacy of incline treadmill running as a training tactic for distance runners, future investigations should challenge the limitations of the current protocol and focus on assessing both over-ground uphill and incline treadmill running at a variety of surface grades, training velocities, bout durations, and total number of high-intensity interval training sessions, while also including, if possible, more specific measures of muscle power output.

Practical Applications

This study validates to a certain extent the long-used practice of uphill running as a training tactic and shows that that a relatively modest amount of high-intensity interval incline treadmill training (10–14 $min \cdot wk^{-1}$) can induce significant improvements in the $\dot{V}O_2$ and BLa responses during submaximal running, as well as the percentage of $\dot{V}O_2max$ attained when running at V_{LT}, factors previously shown to be associated with improved endurance performance (31,46). However, high-intensity interval incline treadmill training does not appear to serve as a substitute for traditional resistance-to-movement exercises; and therefore coaches and athletes should continue to include various strength training and explosive training tactics as part of a comprehensive distance running program. Since performing repeated incline treadmill running bouts on a 10% grade at 100%V_{max} for 30 seconds requires an extreme effort, particular attention must be paid to running form so that poor running mechanics and improper coordination strategies are not developed. An obvious alternative to our investigation's G_{Hill} protocol would be performing longer, slower, less intense incline treadmill running bouts at the same surface grade; however, as highlighted in both the introduction and the discussion section, training with near or above maximum intensities designed to elicit maximum muscular contraction and/or velocity when performing resistance-to-movement exercises seems crucial for impacting running performance. As such, we suggest that before engaging in this training practice, individuals have spent considerable time for developing their metabolic, muscular, and neuromuscular systems through a comprehensive approach of high-intensity interval and resistance-to- movement training sessions; and that novice and/or undertrained individuals avoid over-ground uphill or incline treadmill training methods until more physically developed. Furthermore, we also recommend high-intensity interval incline treadmill running be strategically planned into specific 4- to 8-week microcycles of a year-round training program –for example, during that time of year when transitioning training volume and intensity from high-to-low and low-to-high, respectively, in manner similar to those collegiate teams that have reported using it most effectively and successfully (28).

Acknowledgments

The authors thank the participants for their great effort, willingness, and enthusiasm for participating in this study. We also greatly appreciate the technical assistance of Paul Keizer, Sarah Quail, and Mary Thum, and the support of Avera McKennan Hospital and University Health Center. The authors of this study received no funding for this investigation and have no conflicts of interest.

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