

## Effects of Different Uphill Interval-Training Programs on Running Economy and Performance

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**Purpose:** Runners use uphill running as a movement-specific form of resistance training to enhance performance. However, the optimal parameters for prescribing intervals are unknown. The authors adopted a dose-response design to investigate the effects of various uphill interval-training programs on physiological and performance measures. **Methods:** Twenty well-trained runners performed an incremental treadmill test to determine aerobic and biomechanical measures, a series of jumps on a force plate to determine neuromuscular measures, and a 5-km time trial. Runners were then randomly assigned to 1 of 5 uphill interval-training programs. After 6 wk all tests were repeated. To identify the optimal training program for each measure, each runner's percentage change was modeled as a quadratic function of the rank order of the intensity of training. Uncertainty in the optimal training and in the corresponding effect on the given measure was estimated as 90% confidence limits using bootstrapping. **Results:** There was no clear optimum for time-trial performance, and the mean improvement over all intensities was 2.0% (confidence limits  $\pm 0.6\%$ ). The highest intensity was clearly optimal for running economy (improvement of  $2.4\% \pm 1.4\%$ ) and for all neuromuscular measures, whereas other aerobic measures were optimal near the middle intensity. There were no consistent optima for biomechanical measures. **Conclusions:** These findings support anecdotal reports for incorporating uphill interval training in the training programs of distance runners to improve physiological parameters relevant to running performance. Until more data are obtained, runners can assume that any form of high-intensity uphill interval training will benefit 5-km time-trial performance.

**Keywords:** endurance training, resistance training, oxygen consumption, neuromuscular characteristics

Differences in submaximal oxygen uptake exist between athletes running at the same speeds, and these disparities in "running economy" are a major factor explaining differences in running performance of endurance athletes.<sup>1-3</sup> Various strategies such as altitude exposure,<sup>4</sup> training in the heat,<sup>5</sup> dynamic stretching,<sup>6</sup> and high-intensity interval training<sup>1,2,7</sup> have been proposed as methods to improve running economy via their effect on 1 or more of the metabolic, cardiorespiratory, neuromuscular, and musculoskeletal systems. Most recent research has focused on the effects of supplementing endurance training with different forms of heavy-resistance or plyometric training to further improve running economy and running performance.<sup>7-15</sup> While coaches often use various forms of movement-specific resistance training in periodized training programs for distance runners, only anecdotal reports<sup>5,16,17</sup> and 2 research investigations<sup>18,19</sup> exist concerning the physiological responses to and potential improvements in performance from such training. Ferley et al<sup>18</sup> compared effects of uphill interval training and control (level-grade) interval training on

various measures of performance in well-trained distance runners. Although performance in both groups improved substantially, the only significant difference favored control training. Houston and Thomson<sup>19</sup> used a combination of uphill gradients and durations in addition to traditional resistance training in each training session. Despite no changes in  $VO_{2max}$ , they found significant improvements in a time-to-exhaustion test, as well as increased distance run in 60- and 90-second timed runs. The authors did not report running economy in either study.

In view of the uncertainty about the physiological effects of uphill training and other movement-specific forms of resistance training on distance-running performance, there is a clear need for more research in this area to identify optimal training.<sup>7</sup> The conventional approach to investigating an optimal treatment is to perform a repeated-measures crossover study, with each subject receiving all treatments. However, this approach is often impractical in training studies, because the long-lasting effects of training prevent subjects from receiving more than 1 type of training. To address this problem, Stepto et al<sup>20</sup> reported a novel and potentially more powerful dose-response design, in which individual cyclists received only a single form of training and the optimal training "dose" was identified by modeling the effect of training as a polynomial function of the rank-ordered training intensity. In

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the current study, we adopted the same modeling approach in an attempt to determine the uphill interval-training protocol most effective for running economy and performance in well-trained distance runners.

## Methods

### Design

We adopted a pre–post parallel-groups design with measures conducted before and after a 6-week intervention period. Subjects reported to the laboratory at least 2 hours postprandial and having avoided strenuous exercise in the 24 hours preceding all test sessions. Before the intervention, subjects performed baseline measures of the dependent variables on 2 occasions separated by 3 days. The first testing session included an incremental treadmill test to determine aerobic and biomechanical characteristics, followed by a series of jumps to determine muscle-power characteristics. The second testing session took place 3 days later and involved a 5-km outdoor time trial. Four days after completing the final training session, each runner repeated the same set of tests in the same order as preintervention testing.

### Subjects

Twenty distance runners (mean  $\pm$  SD; age  $21 \pm 4$  y, body mass  $65 \pm 8$  kg, height  $178 \pm 9$  cm) with an average 5-km-race personal-best time of  $16.5 \pm 1.2$  min, average weekly training volume of  $95 \pm 25$  km/wk, and training history of  $6.3 \pm 2.9$  years were randomly assigned to 1 of 5 uphill interval programs. The intervention training-adherence rate for participants was 100%. As running volume was not manipulated in the current study, subjects in all groups continued with their normal running over the course of the study, with the addition of the intervention substituting some of their normal running for interval training. Training logs for all subjects were monitored before and during the training. It was a requirement of the study that participants had not undertaken any structured interval training or resistance training in the previous 6 weeks. The study was approved by the institutional ethics committee and all participants provided informed written consent.

### Treadmill Testing

All running tests were performed in a temperature-controlled laboratory ( $19$ – $21^\circ\text{C}$ , 65% relative humidity) on a motorized treadmill (PowerJog, Birmingham, UK) set at a 1.0% gradient.<sup>3</sup> After a standardized warm-up, subjects completed an incremental test to determine running economy, involving repeated, progressively faster (increments of 1.0 km/h) 4-min stages at 4 to 6 fixed running speeds ranging from 12 to 18 km/h until they were unable to sustain steady-state  $\text{VO}_2$ . A 90-second recovery period occurred between stages for blood lactate sampling (Lactate Pro, Arkray, Japan) for later determination of lactate threshold (D-max method).<sup>21</sup> Expired

gases were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, UT, USA) for determination of  $\text{VO}_2$ ,  $\text{VCO}_2$ ,  $\text{V}_E$ , and RER. Heart rate was determined every 1 s (Polar RS800sd, Polar Electro, Finland). Running economy was defined as the mean  $\text{VO}_2$  determined during the last minute of each running speed. Approximately 90 seconds after completion of the final submaximal running stage,  $\text{VO}_{2\text{max}}$  was determined during an incremental test to volitional exhaustion. Subjects commenced running at 1.0 km/h (1.0% gradient) below the final submaximal speed for 1 minute. Thereafter, treadmill gradient was increased by 1% each minute until volitional exhaustion. The highest  $\text{VO}_2$  over a 30-second period during the test was considered  $\text{VO}_{2\text{max}}$ . Changes in endurance performance were indicated by the peak running speed reached at the end of the incremental treadmill test. Because we used increases in gradient (rather than speed) in the latter part of the treadmill test, we calculated speed on the flat as  $S = S_T + (S_T \times 0.045) \times i$ , where  $S$  = peak speed in km/h,  $S_T$  = treadmill speed in km/h, and  $i$  = treadmill inclination in percent.<sup>22</sup>

### Neuromuscular Measures on a Force Plate

After a 30-minute passive recovery period, subjects performed a countermovement jump and squat jump as previously described by McGuigan et al<sup>23</sup> and a 5-jump plyometric test described by Saunders et al<sup>12</sup> on an AccuPower force plate (Advanced Mechanical Technology Inc, Watertown, MA) to determine neuromuscular characteristics. Each jumping test was performed twice. The following parameters were determined for each type of jump: peak force, time to peak force, peak power, maximum rate of force development, displacement, eccentric utilization ratio, and stiffness. Eccentric utilization ratio was calculated as the peak power ratio between performances on the countermovement jump compared with the squat jump.<sup>23</sup> Stiffness was estimated by dividing the peak force by the vertical displacement measured during the 5-jump test.<sup>24</sup>

### Running Performance

Three days after laboratory-based tests, subjects completed a 5-km self-paced time trial on a 400-m outdoor tartan track. After each subject's typical self-chosen precompetition warm-up (recorded and repeated postintervention), he or she was instructed to run the distance "as fast as possible."

### Training Interventions

Subjects performed 2 uphill interval-training sessions/wk over a 6-week period while maintaining their normal running training outside of the weekly interval-training sessions. Specific details of the work:rest ratios, intensity, and uphill gradient of the different training interventions are presented in Table 1. The work:rest ratios were not

**Table 1** Details and Progression of the Five 6-Week Uphill Interval-Training Programs (2 Interval-Training Sessions/Wk)

	Group 1 (n = 3)	Group 2 (n = 5)	Group 3 (n = 5)	Group 4 (n = 4)	Group 5 (n = 3)
Gradient	18%	15%	10%	7%	4%
%HR <sub>max</sub>	100%	100%	98–100%	93–97%	88–92%
Velocity at VO <sub>2max</sub>	120%	110%	100%	90%	80%
Work:rest ratio	1:6	1:3	1:2	1:1.5	1:1
Progression					
week 1	12 × 8 s	8 × 30 s	5 × 2 min	4 × 4 min	2 × 10 min
week 2	16 × 10 s	10 × 35 s	5 × 2.5 min	4 × 5 min	2 × 15 min
week 3	20 × 10 s	12 × 40 s	7 × 2 min	5 × 4.5 min	1 × 20 + 1 × 15 min
week 4	20 × 12 s	12 × 45 s	7 × 2.5 min	5 × 5 min	2 × 20 min
week 5	24 × 10 s	16 × 40 s	9 × 2 min	6 × 5 min	3 × 15 min
week 6	24 × 12 s	16 × 45 s	9 × 2.5 min	7 × 5 min	2 × 25 min

consistent with standard interval-training practice<sup>7</sup> but were designed to accommodate the practicalities of uphill interval training, when runners have to return to the bottom of a hill to start another repetition. The outcomes are therefore more likely to reflect what athletes should expect when they add uphill running to their training program.

### Statistical Analysis

We performed simulations to determine the sample size that would give an acceptable confidence interval for optimal performance predicted with a quadratic dose-response model. In these simulations, the training protocol was a variable that ranged from 1 for the highest intensity and shortest duration through 5 for the lowest intensity and longest duration. Data were generated that had no real polynomial effects, because data without effects need the largest sample sizes to define the magnitude of the effects with acceptable precision. With 20 subjects, an error of measurement for an individual's running economy of 2%, and a quadratic model, the 90% confidence interval was acceptable.

All performance and other outcome measures were analyzed as percentage changes via the transformation  $\log[(\text{post measurement})/(\text{pre measurement})]$ .<sup>25</sup> The transformed data were modeled as a quadratic function of the rank-ordered intensity of the training protocols to determine the optimal training dose and the value of the change in the outcome measure at this dose.<sup>26</sup> The standard error of the estimate from the model divided by the square root of 2 provided an estimate of the error of measurement for the outcome measure under the conditions of the experiment (after adjustment for the dose-response relationship). Confidence intervals for the measures derived from the quadratic model were generated by bootstrapping using a customized Excel spreadsheet.<sup>27</sup> For the value of the change in the outcome measure at the optimal dose, bootstrapping also provided

estimates of the probabilities that the true change was greater or less than the smallest important beneficial and harmful change.

To make conclusions about the true effects of training on performance and other outcome measures, we used the clinical form of magnitude-based inference: Unclear effects were those with the possibility (>25% chance) of benefit but an unacceptable risk of harm (odds ratio of benefit to harm <67).<sup>28</sup> All other effects were clear and reported with a qualitative probability for the true magnitude using the following scale: 25% to 74%, possibly; 75% to 94%, likely; ≥95%, very likely. This approach to inference requires an estimate for smallest important change in each outcome measure. The smallest enhancement of performance that has a substantial effect on an athlete's chance of improvement is 0.3 of the typical within-athlete variation of performance between competitions.<sup>25</sup> The variability of performance of high-level competitive distance runners (3–10 km) is 1.1%<sup>29</sup>; consequently, a smallest important change of 0.3% was used for measures of performance.

To analyze potential mechanisms underlying the effect of training on performance, changes in performance were plotted against changes in physiological and other measures and the scatterplots inspected for any linear trend. A clear linear trend in the graph would have allowed for estimation of the smallest important change in the mechanism variable as the change that tracked the smallest important change in performance. However, there were no such clear linear relationships, presumably because random error of measurement masked any relationship between real individual differences in changes in performance and the mechanism variable. A different approach to estimating smallest changes was therefore adopted. The enhancement in performance turned out to be practically constant across the range of training intensities (~2%). Therefore, to estimate the smallest important change in each mechanism variable,

we assumed that the tracking of changes in the means of the mechanism and performance variables reflected the underlying relationship in the individual change scores. The smallest important change in the mechanism variable was therefore  $0.3\% \times (\Delta \text{ mechanism})/(\Delta \text{ performance})$ , where  $\Delta$  is the change in the mean; for example, the smallest important change in  $\text{VO}_{2\text{max}}$  was calculated as  $0.3\% \times (4.1/2.0) = 0.62\%$ .

## Results

Figure 1 shows the percentage change and quadratic trends for identifying optimal training intensity with bootstrapped confidence limits for performance and selected other measures for the individual subjects in the rank-order intensity of each group after the uphill interval-training intervention. Table 2 shows baseline values of outcome measures and statistics from the bootstrap analyses for inferences about the optimal intensity and duration of interval training and about the effects on the outcome measures at the optimum. A well-defined outcome for the effect of dose of training on outcome measures present in Table 2 was shown if the proportion of successful bootstrap simulations (bootstrap success rate) was  $\geq 90\%$  and there was a reasonable confidence interval associated with the dose (group) or the confidence interval was limited to 1 of the dose extremes (ie, 1, 1 or 5, 5). Errors of measurement derived from the modeling are also shown in Table 2 and allow assessment of the precision of the measures in comparison with those in reliability studies (see Discussion).

Data for the 5-km time trial showed a weak quadratic trend (Figure 1). The modeling predicted an optimum near the middle of the range of training intensity and duration (group = 2.3, as shown in Table 2) and a likely beneficial effect on performance ( $-2.0\%$ ). However, the bootstrap success rate (57%) represents inconsistency in the curvature of the bootstrapped quadratics; that is, only 57% predicted a minimum in performance time, and the resulting confidence interval for the optimal treatment extended to both extremes of the treatment range (1–5). Changes in peak speed showed similar results.

There was a strong trend toward groups 3 and 4 having the optimal training parameters to improve all aerobic measures besides running economy (Figure 1, Table 2). There were well-defined outcomes for the effects on aerobic measures obtained during the incremental treadmill test (bootstrap success rate  $\geq 90\%$ ), indicating consistency in predicting a maximum at the turning point. Most of the aerobic measures had reasonably narrow confidence limits for the training intensity (ie, group), and the 2 running-economy measures had an optimum precisely defined at the highest intensity (group 1; Table 2). The effects at the optima were also clear. Improvements in all aerobic measures except running economy were made across groups 2 through 5, with the optima occurring

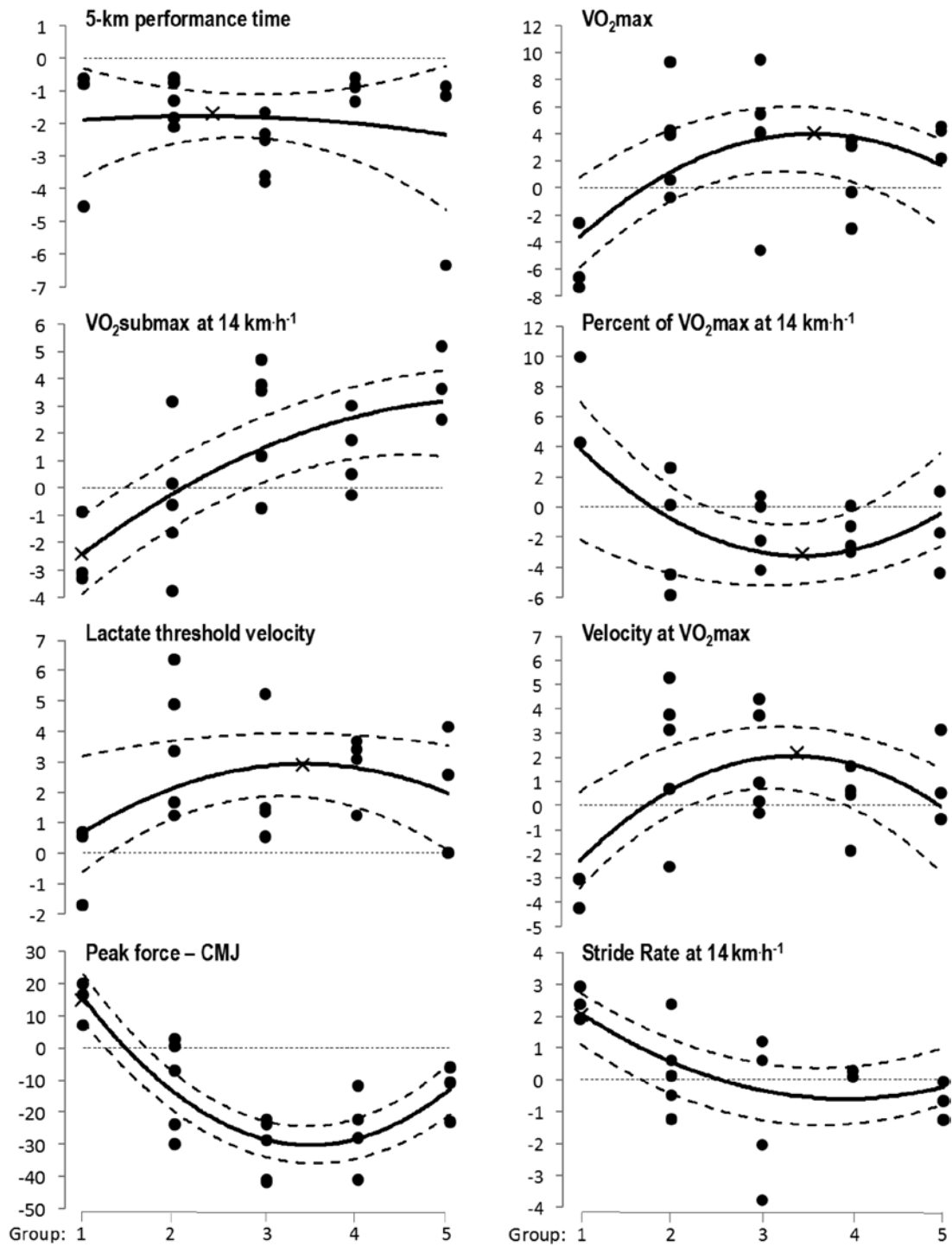
near the middle of this range, whereas group 1 showed a negative effect in most aerobic measures. However, the reverse phenomena occurred for running economy, where the effects only showed improvements in group 1 (Figure 1).

Improvements in biomechanical measures (Figure 1—stride rate, Table 2) favored groups 1 to 3 (Table 1). Bootstrap success rate was variable from measure to measure. Accordingly, the confidence limits for the training intensity and effects reflect this with narrow confidence limits around measures with well-defined outcomes (bootstrap success rate  $\geq 90\%$ ) and wide confidence limits around those without well-defined outcomes (low bootstrap success rate, Table 2). All improvements in muscle-power measures favored group 1 (Table 2), and the changes across all groups were similar to that of countermovement-jump peak force shown in Figure 1. There was a high bootstrap success rate for the eccentric utilization ratio, stiffness, peak force, time to peak force, and maximum rate of force development of all 3 jumps ( $\geq 85\%$ ), and a low rate in the peak-power measurements of all 3 jumps ( $\leq 36\%$ ). Where confidence limits were narrow for the optimal-training group, so were the confidence limits for the effects at the optima. Inferences about the effects on performance and other outcome measures showed likely or very likely benefit at the predicted optima.

## Discussion

In the current study we used a novel design and analysis approach, previously adopted by Stepto et al,<sup>20</sup> to determine the effects of different types of uphill interval-training programs on running economy and performance in trained distance runners. A major finding was that no specific uphill-training approach was associated with greater gains in 5-km time-trial performance, but curvilinear relationships existed between a continuum of hill-training approaches on several performance-related physiological variables including running economy (Figure 1). Running performance improved across the range of training intensities without a strong curvilinear relationship between uphill-training characteristics and a subsequent change in 5-km time-trial performance or peak running speed. The 2% improvement in running performance was similar to other studies demonstrating concurrent improvements in running economy and performance while employing various modes of resistance training.<sup>10,13</sup> Ferley et al<sup>18</sup> also demonstrated an  $\sim 2\%$  improvement in estimated time-trial performance<sup>30</sup> after 6 weeks of uphill interval training similar to group 2 training in the current study.

The error of measurement derived from the bootstrap analysis for 5-km time-trial performance was 1.2%, which is comparable to other studies employing true reliability studies with well-trained distance



**Figure 1** — Percentage change in performance and selected physiological measures after the 5 uphill interval-training programs. Black dots represent individual changes in runners. Solid curved line represents mean from quadratic modeling, and dashed curved lines are the associated confidence limits generated from bootstrapping. × = the predicted group optimum; CMJ = countermovement jump.



**Table 2 Outcome Measures at Baseline and Statistics From the Bootstrap Analyses for Inferences About the Effects at the Predicted Group Optimum**

	Baseline values (mean ± SD)	Error <sup>a</sup> (%)	Bootstrap success rate (%)	Predicted Optimal Group and Corresponding Effect (90%CL)	
				Group <sup>b</sup>	Effect (%)
Running performance					
5-km performance time	17.0 ± 1.3 min	1.2	57	2.3 (1, 5)	-2.0 (-2.5, -1.3)*
peak speed	21.4 ± 1.9 km/h	1.2	54	3.1 (1, 5)	2.0 (1.8, 3.7)**
Aerobic measures					
VO <sub>2max</sub>	63.9 ± 5.9 mL · kg <sup>-1</sup> · min <sup>-1</sup>	3.0	96	3.6 (2.9, 4.6)	4.1 (2.2, 6.6)**
vVO <sub>2max</sub>	18.7 ± 1.5 km/h	1.7	98	3.4 (2.7, 4.1)	2.0 (1.0, 3.4)**
lactate threshold velocity	15.9 ± 1.6 km/h	1.4	91	3.4 (2.2, 5)	2.9 (2.3, 4.2)**
VO <sub>2submax</sub> @ 14 km/h	53.7 ± 3.0 mL · kg <sup>-1</sup> · min <sup>-1</sup>	1.5	90	1 (1, 1)	-2.4 (-3.9, -1.0)**
VO <sub>2submax</sub> @ 14 km/h	201 ± 11 mL · kg <sup>-1</sup> · min <sup>-1</sup>	1.5	90	1 (1, 1)	-2.4 (-3.9, -1.0)**
% of VO <sub>2max</sub> @ 14 km/h	84.4 ± 7.6% VO <sub>2max</sub>	3.0	96	3.5 (1.9, 4.4)	-3.2 (-6.2, -1.9)*
Biomechanical measures					
stride rate	87.8 ± 4.5 strides/min	1.0	93	1 (1, 1)	2.1 (0.9, 2.7)**
stride length	3.03 ± 0.21 m	1.7	64	2.3 (1, 5)	0.4 (0.0, 2.3)*
contact time	0.22 ± 0.02 s	3.0	88	3.1 (1, 5)	-5.2 (-8.0, -3.9)**
flight time	0.12 ± 0.02 s	6.1	91	3.4 (2.8, 5)	10 (6, 18)**
Neuromuscular measures					
eccentric utilization ratio	1.03 ± 0.06	2.2	98	1 (1, 1)	12 (8, 16)**
stiffness	11.0 ± 2.5 kN/m	3.5	85	1 (1, 1.8)	25 (8, 39)**
Countermovement jump					
peak force	63 ± 19 N/kg	7.7	100	1 (1, 1)	15 (9, 24)**
time to peak force	1.82 ± 0.47 s	13	92	1 (1, 3.2)	7.2 (-2, 29)*
peak power	42.6 ± 6.3 W/kg	7.5	36	1 (1, 5)	2.6 (-4.1, 8.8)*
maximum RFD	101 ± 50 kN/s	20	100	1 (1, 5)	29 (6, 52)**
Squat jump					
peak force	58 ± 14 N/kg	7.7	100	1 (1, 1)	12 (7, 22)**
time to peak force	2.04 ± 0.69 s	12	92	1 (1, 1)	-7.5 (-16, 4)*
peak power	43.9 ± 6.0 W/kg	7.9	12	1 (1, 5)	-3.9 (-11, 2)?
maximum RFD	94 ± 34 kN/s	12	99	1 (1, 1)	19 (13, 29)**
5-jump test					
peak force	64.5 ± 5.4 N/kg	7.7	96	1 (1, 1)	8.4 (-1, 13)**
time to peak force	2.75 ± 0.71 s	15	99	1 (1, 1)	-22 (-33, 0)**
peak power	69 ± 13 W/kg	7.6	29	1 (1, 5)	4.5 (-2, 10)*
maximum RFD	105 ± 47 kN/s	20	97	1 (1, 3.6)	21 (-5, 48)*

Abbreviations: CL, confidence limits; VO<sub>2max</sub>, maximal aerobic capacity; vVO<sub>2max</sub>, velocity at VO<sub>2max</sub>; RFD, rate of force development.

<sup>a</sup> Error of measurement derived from the bootstrap analysis (which adjusts for any quadratic effect of group and thereby provides an estimate of error approximating the typical error in a 6-wk reliability study without an intervention). <sup>b</sup> Group range = 1–5 (Table 1). For example, 2.3 indicates that the optimal training fell between groups 2 and 3 and therefore had an intensity of 100–110% (of vVO<sub>2max</sub>), a duration of 30–120 s, and a gradient of 10–15%.

\*Likely beneficial. \*\*Very likely beneficial. ?Unclear.

runners,<sup>29,31,32</sup> suggesting to us that there is limited evidence for individual responses to training. The correlations between percentage changes in 5-km performance and percentage changes in each of the aerobic, biomechanical, neuromuscular, and peak-speed measures were unclear. A lack of clear correlations provides additional support for no individual responses to explain. However, because every participant demonstrated some sort of improvement in 5-km time-trial performance it can be suggested that running performance can be enhanced as a result of changes in a variety of mechanistic variables caused by varying the uphill-running loading parameters.

With regard to effect of uphill interval training on improvements on selected aerobic, neuromuscular, and biomechanical measures, the various 6-week uphill interval-training programs resulted in curvilinear trends, often with an identified optimum (Figure 1). There was a well-defined outcome for the effect of dose of training on all aerobic measures and most biomechanical and neuromuscular measures. A larger sample size would be needed to establish clear optima for the other outcomes. Except for improvements in running economy, our model predicted optimal enhancements after work bouts associated with an intensity between groups 3 and 4 training (Table 1). The enhancements observed for aerobic measures (Table 2) besides running economy are perhaps unsurprising, since the intensity of these work bouts occurred at or near  $VO_{2max}$ , which is in accord with the principle of specificity. It is highly likely these changes were a result of the additional uphill interval training because all subjects were undertaking similar running training outside of the current study ( $95 \pm 25$  km/wk). In contrast, the 2 studies utilizing uphill interval training reported no change<sup>19</sup> or a decrement in  $VO_{2max}$ .<sup>18</sup>

We observed that training at the highest intensities (group 1 and 2) was associated with the greatest improvements in running economy and neuromuscular characteristics, as well as increased stride rate. Ours is the first study to demonstrate that a regimen of high-intensity uphill interval training improves running economy. The magnitude of the improvement (2.4%) is consistent with previous studies reporting positive effects of traditional resistance training or plyometric training on running economy in runners with a wide range of ability,<sup>8-15</sup> as well as anecdotal reports of the benefits of uphill sprinting.<sup>5,16,17</sup> The observed improvement in running economy was accompanied by similar reduction in  $VO_{2max}$  and consequently an increase in  $\%VO_{2max}$  in group 1 (Figure 1). This is not surprising given that the training imposed on athletes in group 1 (Table 1) would be unlikely to augment  $VO_{2max}$  in any way. It is known a positive relationship exists between maximal and submaximal  $VO_2$ , indicating that athletes with higher aerobic demands of running (ie, poorer running economy) tend

to have higher  $VO_{2max}$  values, which may also explain the positive shift in running economy and negative shift in  $VO_{2max}$ .<sup>33-36</sup> The theoretical underpinnings of this observation have yet to be fully elucidated but may relate to various neuromuscular and/or biomechanical characteristics. It should be noted that regardless of the changes in running economy,  $VO_{2max}$ , and  $\%VO_{2max}$ , group 1 training still resulted in an ~2% improvement in 5-km run performance (Figure 1).

The fact that the greatest improvements in neuromuscular measures also occurred with the highest intensity of training (Table 2) may support the aforementioned premise that the enhancement of running economy was due to a range of mechanisms relating to recruitment and coordination of muscle fibers and efficiency of muscle power development, as well as better use of the muscle-tendon units' stored elastic energy. An indirect measure of this storage and return of muscular energy is the eccentric utilization ratio, in which we found 12% improvements in group 1 training (Table 2). Another key function of the active skeletal musculature during running is to regulate the stiffness of the muscle-tendon apparatus to maximize the exploitation of elastic energy, which improves running economy.<sup>24</sup> Like other neuromuscular characteristics, leg stiffness measured in this study showed the greatest improvements at the highest training intensity (Table 2). The error of measurement for neuromuscular measures in Table 2 adds some uncertainty to the true relationship between training dose and effect but is not unreasonable, given that the measured error is population specific and is still comparable to other reliability studies.<sup>37</sup> The improvements in neuromuscular measures are also in agreement with a number of other studies using various forms of explosive resistance training or plyometric type of activities such as hopping, jumping, and bounding as ways to directly or indirectly potentiate neuromuscular adaptations.<sup>10-13,15</sup>

Finally, another plausible explanation for improved running economy after high-intensity uphill interval training is training-induced alteration in stride rate, which was also greatest at the highest intensity of training (Figure 1, Table 2). Paavolainen et al<sup>10</sup> observed similar changes in stride characteristics in response to 9 weeks of explosive strength training in well-trained endurance runners along with concurrent ~8% improvement in running economy. The changes in biomechanical measures may themselves be explained at least partly by changes in neuromuscular characteristics.

## Practical Applications and Conclusion

Our findings provide support for incorporating uphill interval running in the training programs of distance runners to improve various physiological, biomechanical,

and neuromuscular parameters relevant to running performance. Different uphill-training approaches appear to induce specific physiological and mechanical adaptations, which suggests that hill training should be carefully matched to the strengths and weaknesses of the athlete, the underlying demands of the event, and the training or competitive focus. Until more data are obtained, runners can assume that performance enhancements can be made as a result of changes in a variety of mechanistic variables caused by varying the uphill-running loading parameters, since every participant demonstrated some sort of improvement in 5-km time-trial performance. Further studies are required to establish whether improvements derived from uphill interval training can be established through variations in the frequency, duration, volume, and periodization of training.

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