

The metabolic costs of walking and running up a 30-degree incline: implications for vertical kilometer foot races

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Abstract

Purpose Vertical kilometer (VK) races, in which runners gain 1000 m of elevation in <5000 m of distance, are becoming popular. However, few studies on steep uphill running (>25°) exist. Previously, we determined that ~30° is the optimal angle for uphill running, costing the least amount of metabolic energy for a specific vertical velocity. To inform the training and strategy of VK racers, we quantified the metabolic cost of walking and running at various velocities up a 30° incline.

Methods At 30°, 11 experienced runners (7 M, 4 F, 30.8 ± 7.9 years, 1.71 ± 0.08 m, 66.7 ± 9.4 kg) walked and ran for 5-min trials with 5-min rest between. Starting at 0.3 ms⁻¹, we increased treadmill velocity by 0.1 ms⁻¹ for each trial until subjects could not maintain the set velocity. We measured oxygen uptake (ml O₂ kg⁻¹ min⁻¹) and metabolic power (W kg⁻¹ = metabolic energy per unit time per unit body mass) and calculated metabolic costs of walking (C_w) and running (C_r) per unit distance (J kg⁻¹ m⁻¹).

Results Oxygen uptake and metabolic power increased linearly with velocity. Between 0.3 and 0.7 ms⁻¹, C_w < C_r. At 0.8 ms⁻¹ there was no difference and extrapolation suggests that at faster velocities, running likely costs less than walking.

Conclusion On a 30° incline, metabolic power increases linearly with velocity. At speeds slower than 0.7 ms⁻¹, walking requires less metabolic power than running (W kg⁻¹) suggesting most VK racers should walk rather than run.

Keywords Uphill · Cost of transport · Energetics · Economy

Abbreviations

CVKT	Colorado vertical kilometer test
C _w	Metabolic cost of walking (J kg ⁻¹ m ⁻¹)
C _r	Metabolic cost of running (J kg ⁻¹ m ⁻¹)
RER	Respiratory exchange ratio
VK	Vertical kilometer

Introduction

The vertical kilometer (VK), a foot race in which runners gain 1000 m of elevation over a course length of less than 5000 m (International Skyrunning Federation: <http://www.skyrunning.com>), has rapidly gained popularity in recent years. The VK records for men and women were both set on a course with an average incline of 31.4° (61.0%) (km vertical de Fully, Switzerland). The men's VK world record of 29:42, set by Urban Zemmer, equates to an average running velocity of 1.08 m·s⁻¹, or an average vertical velocity of about 0.56 m·s⁻¹. Because extremely steep uphill running races have only recently become popular, there have been few scientific studies of the biomechanics and physiology of the VK.

Minetti et al. (2002) established that for both walking and running at a given steep incline, up to 24.2° (45%), metabolic power (W kg⁻¹ = metabolic energy per unit

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time per unit body mass) increases linearly with treadmill velocity. Further, they found that at a given treadmill velocity, metabolic power increases linearly with the sine of the incline angle for slopes between 0° and 24.2° . Hoogkamer et al. (2014) found that including an exponentially decaying term related to braking and propelling forces better predicted the metabolic cost of running at angles less than 9° , but the relationship became more linear at steeper angles. Thus, the metabolic cost of running uphill can be mostly explained by the fact that the mechanical power needed to lift one's center of mass is equal to the product of body mass, gravity (9.81 m/s^2), velocity, and the sine of the slope angle θ . If efficiency is constant, metabolic power is proportional to mechanical power.

We recently investigated the “optimal” uphill slope angle for VK races that minimizes the metabolic cost of running per vertical meter ($\text{J kg}^{-1} \text{ m}^{-1}$) and thus maximizes vertical velocity (Giovanelli et al. 2015). For both walking and running, angles ranging from 20.4° to 35.0° minimized the metabolic cost of ascending at a vertical velocity of 0.35 ms^{-1} . We reasoned that VK race courses with slopes in that range should yield the fastest times. Additionally, at 0.7 ms^{-1} on a 30° incline, walking required a 9.2% lower metabolic power than running, suggesting that to minimize metabolic cost, most competitors in a VK should walk rather than run. However, neither Minetti et al. (2002) nor Giovanelli et al. determined how metabolic power changes across a range of velocities at an extreme angle, e.g., 30° . Thus, existing data do not allow for predictions of VK performance based on physiological parameters such as an athlete's oxygen uptake at a specified velocity and maximal rate of oxygen consumption ($\dot{V}\text{O}_{2\text{max}}$) (Joyner 1991).

To inform the training and strategy of VK competitors, our primary goal was to compare the metabolic power (W/kg) for walking and running at one extreme uphill angle (30°) across a range of velocities. We chose to study the metabolic power required for walking and running as close as possible to the men's world record VK pace and angle. From Giovanelli et al. (2015), we knew that at a 30° incline, walking requires less metabolic power than running at a treadmill belt velocity of 0.7 ms^{-1} . Giovanelli et al. calculated the metabolic costs of walking C_{wvert} and running C_{rvert} per meter of vertical distance climbed ($\text{J kg}^{-1} \text{ m}^{-1}$). In the present paper, we calculated the cost of walking and running per meter walked or run along the direction of the treadmill belt, so the values should not be directly compared. Here, we sought to determine whether walking or running is cheaper at faster treadmill belt velocities that are more representative of competitive VK performances. During VK races, slower competitors often walk, while elite racers typically choose to run. Therefore, we hypothesized that at 30° there is a particular velocity, above 0.7 ms^{-1} , at which running requires less metabolic power than walking.

Our second goal was to develop a standardized steep uphill treadmill protocol for testing VK runners. For level running, there are a few such protocols commonly used by scientists to evaluate and compare oxygen uptake at specified velocities. Typically, these protocols entail determining $\text{VO}_{2\text{submax}}$ at between 4.5 and 3.8 ms^{-1} (~ 6 to $7 \text{ min per mile pace}$ or $\sim 3:45$ to $4:20 \text{ min km}^{-1}$) at a 0 or 1% incline (Jones 2006; Farrell et al. 1979; Lucia et al. 2006; Weston et al. 2000; Morgan et al. 1995). Here, we propose an analogous test specifically for VK runners and begin to establish normative values. Eventually, runners who perform this standardized test will be able to compare their uphill running energetics to norms as well as those of elite athletes.

Methods

Subjects

11 healthy runners of varied ability (7 males, 4 females, age: 30.8 ± 7.9 years, height: $1.71 \pm 0.08 \text{ m}$, mass: $66.7 \pm 9.6 \text{ kg}$, body mass index: $22.8 \pm 2.4 \text{ kg m}^{-2}$) volunteered and provided informed consent as per the University of Colorado Institutional Review Board. Subjects ranged from recreational runners to elite mountain runners, who had finished in the top 10% in competitive mountain races.

Treadmill

As described by Giovanelli et al. (2015), we altered a custom treadmill, making it inclinable from 0° to 45° . To increase the treadmill belt's traction, we attached a wide swath of skateboard grip tape (Vicious Tape, Vancouver, BC, Canada). To protect the treadmill motor, we attached three v-belt pulleys to the shaft of the drive roller and hung ropes with weights (about 8 kg) over the pulleys. The weight we attached was enough so that the belt did not move when a subject stood on it while the treadmill motor was off. This added resistance allowed the motor to produce power and maintain a nearly constant treadmill belt velocity.

Experimental design

The study consisted of three sessions. During an initial 30-min familiarization session, each subject alternated between walking and running at a variety of velocities with the treadmill inclined at 30° . Subjects wore a nose-clip and an expired gas analysis mouthpiece during the entire familiarization session. During the second and third visits, subjects either walked (e.g., Day 2) or ran (e.g., Day 3) for a series of 5-min trials. Day 2 and Day 3 were at least 48 h apart. Half of the subjects were randomly assigned to walk

on Day 2 and run on Day 3; the other half did the opposite. We set the initial treadmill velocity at 0.3 ms^{-1} . Then, we incremented the treadmill velocity by 0.1 ms^{-1} for each trial, continuing until subjects could no longer maintain a walk or run at the given velocity. Subjects had 5 min of rest between trials. All 11 subjects were able to complete both the walking and running trials at treadmill velocities of 0.3, 0.4, and 0.5 ms^{-1} . However, at 0.6 ms^{-1} only ten subjects could complete both trials, at 0.7 ms^{-1} only nine subjects could, at 0.8 ms^{-1} only six subjects could, and at 0.9 ms^{-1} only one subject was able to complete both walking and running trials while maintaining a respiratory exchange ratio (RER) < 1.0 .

Metabolic measurements

All metabolic data presented in the paper are gross values. To determine metabolic power during walking and running, we used an open-circuit expired gas analysis system (TrueOne 2400, ParvoMedic, Sandy, UT, USA). Subjects wore a nose-clip and mouthpiece to measure their rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$). We averaged the data of the last 2 min of each trial and calculated metabolic power in W kg^{-1} using the Brockway (1987) equation:

$$P_{\text{met}} = (16.58 \text{ W s ml O}_2^{-1} * \dot{V}O_2 \text{ ml O}_2 \text{ s}^{-1}) + (4.51 \text{ W s ml CO}_2^{-1} * \dot{V}CO_2 \text{ ml CO}_2 \text{ s}^{-1}).$$

Next, we calculated the metabolic cost per distance ($\text{J kg}^{-1} \text{ m}^{-1}$) for walking (C_w) and running (C_r) by dividing metabolic power by treadmill belt velocity. Additionally, we only analyzed data recorded when a subject's RER was < 1.0 .

To determine if there was any slow component of $\dot{V}O_2$ kinetics, for each subject's fastest speed at each gait, we averaged the metabolic power (W kg^{-1}) from min 4 and min 5 separately. Because we found no significant difference between the min 4 and min 5 averages (walking: $p = 0.803$, running: $p = 0.684$) we are confident that our measurements represent steady-state metabolism.

Statistical analysis

Using R-Studio (www.rstudio.com), we conducted Shapiro–Wilks tests for normality to determine if the data were normally distributed. Because they were ($0.076 < p < 0.99$), we performed paired t tests to compare the rates of oxygen uptake, metabolic power and the metabolic costs for walking versus running at each velocity. We used $p < 0.05$ as a criterion of significance. Additionally, we determined simple linear regression equations for our metabolic power data (W kg^{-1}) using R-studio. We determined the linear

regression equations: (1) based on all of the data up to 0.9 ms^{-1} ($n = 11$), (2) based on all of the data up to 0.7 ms^{-1} ($n = 9$), and (3) using only the data from subjects who were able to complete all speeds up to 0.8 ms^{-1} ($n = 6$).

Results

Energetics of walking vs. running at 30°

As seen in figure, metabolic power (W kg^{-1}) increased linearly with velocity during both walking and running. At the five slowest velocities, the metabolic power and metabolic cost per distance ($\text{J kg}^{-1} \text{ m}^{-1}$) (Fig. 2) for walking were statistically less than that for running at 0.3 ms^{-1} ($n = 11$), 0.4 ms^{-1} ($n = 11$), 0.5 ms^{-1} ($n = 11$), 0.6 ms^{-1} ($n = 11$), and 0.7 ms^{-1} ($n = 9$) (all $p < 0.004$). However, at 0.8 ms^{-1} there was no statistical difference between the two gaits ($n = 6$; $p > 0.1$). At 0.9 ms^{-1} , only one subject (an elite mountain runner) was able to both walk and run fully aerobically, so it was not possible to statistically compare the two gaits (Table 1).

As shown in Fig. 2, the metabolic cost per distance ($\text{J kg}^{-1} \text{ m}^{-1}$) for both walking and running decreased at faster velocities, at least until 0.9 ms^{-1} . Thus, on a 30° incline for either walking or running it requires less energy per unit distance to travel faster rather than slower.

Discussion

Our primary finding was that on a 30° incline, for both walking and running, metabolic power (W kg^{-1}) increased linearly with velocity (Fig. 1). Intuitively that makes sense; moving faster requires a faster energy supply. Additionally, we found that on a 30° incline, for treadmill velocities between 0.3 and 0.7 ms^{-1} , the metabolic power for walking was significantly less than for running. However, at 0.8 ms^{-1} the metabolic power required for walking and running converged and there was not a significant difference between the two gaits. Only one of our subjects was able to complete the walking and running trials at 0.9 ms^{-1} aerobically, so although running was numerically less expensive than walking for that subject at that speed, we cannot accept our first hypothesis yet. Extrapolation of our data to velocities faster than we could test suggests that running would require less metabolic power, but confirmation awaits further testing on higher caliber athletes. Recall that the world record for the VK race is just under 30 min at a running velocity of 1.08 ms^{-1} on a $\sim 30^\circ$ incline. Because not all of our subjects were able to run/walk at the faster velocities, we chose to analyze our data in three ways, each based on a different number of subjects. For each of the three ways,

Table 1 Oxygen consumption, metabolic power, and cost of transport values for walking (C_w) and running (C_r)

Velocity (m/s)	<i>n</i>	Walk oxygen consumption (ml/kg/min)	Walk metabolic power (W/kg)	C_w (J/kg/m)	<i>n</i>	Run oxygen consumption (ml/kg/min)	Run metabolic power (W/kg)	C_r (J/kg/m)
0.30	11	25.04 ± 1.24*	8.60 ± 0.59*	28.26 ± 1.37*	11	30.63 ± 2.93	10.30 ± 1.17	34.77 ± 3.42
0.40	11	29.84 ± 1.30*	10.29 ± 0.76*	25.30 ± 1.06*	11	35.96 ± 2.42	12.07 ± 1.00	30.63 ± 2.02
0.50	11	35.28 ± 1.31*	12.21 ± 0.93*	24.02 ± 0.84*	11	41.36 ± 2.38	13.92 ± 0.92	28.27 ± 1.64
0.60	11	41.71 ± 1.65*	14.51 ± 1.05*	24.24 ± 1.08*	11	47.16 ± 2.90	16.02 ± 1.02	27.01 ± 1.77
0.70	10	47.94 ± 2.19*	16.50 ± 0.77*	23.67 ± 1.08*	9	52.03 ± 2.83	17.87 ± 0.96	25.63 ± 1.41
0.80	6	55.22 ± 2.64	19.16 ± 0.96	23.95 ± 1.20	8	56.87 ± 2.34	19.72 ± 0.86	24.65 ± 1.08
0.90	1	61.27	21.34	23.71 ± 0.00	1	60.11	20.59 ± 0.00	22.88

Oxygen consumption (ml kg⁻¹min⁻¹), metabolic power (W kg⁻¹) and cost of transport (J kg⁻¹m⁻¹) are reported as mean ± SD

Asterisks (*) indicate a statistically significant difference between walking and running at that velocity

we determined the linear regression between metabolic power (W kg⁻¹) and velocity, v (ms⁻¹). For the first relationship (Eq. 1) we included all of our data, from every velocity and each subject. Next, for Eq. 2, we only used data up to 0.7 ms⁻¹ because at this velocity most subjects ($n = 9$) could run/walk. Finally, for Eq. 3, we used only the data from the six subjects who completed all velocities up to 0.8 ms⁻¹. The equations for running are as follows:

$$\text{Metabolic power run at } 30^\circ = 18.572 V + 4.890 \quad R^2 = 0.927, \quad (1)$$

$$\text{Metabolic power run at } 30^\circ = 18.605 V + 4.889 \quad R^2 = 0.887, \quad (2)$$

$$\text{Metabolic power run at } 30^\circ = 18.521 V + 5.1530 \quad R^2 = 0.929. \quad (3)$$

Although each of these equations is slightly different, they each show that at 30°, as running velocity increases, metabolic power (W kg⁻¹) also increases. The corresponding 90% confidence intervals for the slopes were as follows: (1) [17.45, 19.69], (2) [16.90, 20.31], and (3) [17.04, 20.01]. The corresponding 90% intervals for the intercepts were as follows: (1) [4.25, 5.52], (2) [4.00, 5.77], and (3) [4.30, 6.01]. The similarity of the slopes, intercepts, R^2 values, and 90% CI intervals for Eqs. 1 and 3 despite the different sample sizes supports the validity of our results for 0.8 ms⁻¹.

Furthermore, the calculated cross-over velocity, at which the metabolic power (W kg⁻¹) is less for running than for walking, differs based on which of the above Eqs. (1)–(3) is used for analysis. Based on all of our experimental data, the cross over would be at 0.9 ms⁻¹, based on Eq. 2 it would be at 1.85 ms⁻¹, and based on Eq. 3 it would be at 1.2 ms⁻¹. Obviously, the exact cross-over velocity is unclear at this point. Thus, we also used an additional method for comparing the metabolic power for walking vs. running. We calculated the average percent difference between the

metabolic power for the two gaits at each velocity for all of the subjects who completed testing at that velocity (Fig. 2). We found that walking was 20.6% cheaper at 0.3 ms⁻¹ but only 2.8% cheaper at 0.8 ms⁻¹. This supports the idea that as velocity increases, the metabolic powers required for the two gaits converge, and should eventually cross over. At the slower velocities, the lone subject who could complete 0.9 ms⁻¹ trials used less metabolic power to walk vs. run, but at 0.9 ms⁻¹ he required less metabolic power to run.

It has been argued that on inclines steeper than 9°, the primary determinant of metabolic power is the mechanical power required to lift the body against gravity (Minetti et al. 2002). When running up steep inclines, delta efficiency, the ratio of the increase in mechanical power to the increase in metabolic power, appears to be nearly constant. Therefore, metabolic power increases directly with velocity on a given steep incline. However, if one calculates gross efficiency based on our data at each velocity, it appears to increase from about 14.1% at 0.3 ms⁻¹ to 19.8% at 0.8 ms⁻¹. This increase in efficiency is an artifact of the large zero velocity intercept obvious in Fig. 1. If one calculates the delta efficiency between any two velocities, the values are nearly the same, averaging 25.1%.

Our experimental design (30° at multiple velocities) revealed one counterintuitive finding. We found that at faster velocities, the metabolic cost per distance (J kg⁻¹ m⁻¹) for both walking and running decreased (Fig. 3). This suggests that during VK running, to ascend to a certain peak, a smaller amount of energy is required if the person ascends faster rather than slower. However, the human body has stores of energy substrates (carbohydrates and fats) and VK athletes are generally limited by the rate of oxygen or metabolic energy consumption (i.e., metabolic power).

For level running, plots of metabolic power vs. velocity have relatively small y-intercepts and as a result, the metabolic cost per distance (J kg⁻¹ m⁻¹) for running is

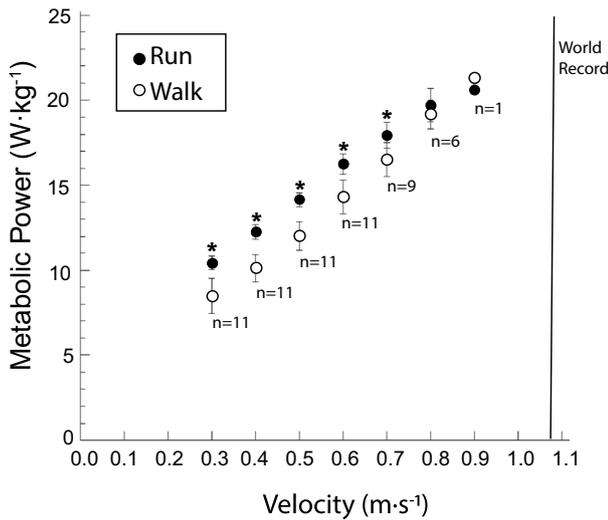


Fig. 1 Metabolic power ($W \cdot kg^{-1}$) as a function of treadmill velocity (ms^{-1}) at a 30° incline. Asterisks (*) indicate a statistically significant difference between walking and running at that velocity ($p < 0.05$). Error bars show SD

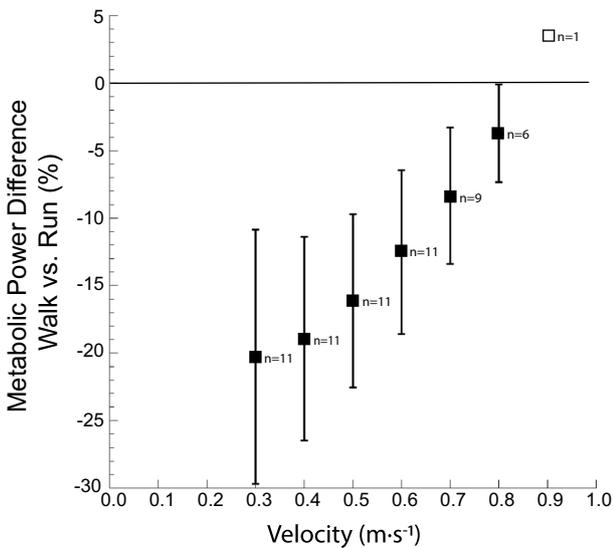


Fig. 2 Average percent difference (%) between the metabolic power required for walking and running ($W \cdot kg^{-1}$) at a 30° incline. Error bars show the SD

fairly constant across velocities. However, for steep uphill running, the y-intercept is substantial. The high metabolic cost per distance ($J \cdot kg^{-1} \cdot m^{-1}$) at slow velocities up steep inclines is mathematically due to large relative contribution of the y-intercept. Unfortunately, the biomechanical or physiological mechanism responsible for the y-intercept is unknown for either level or steep uphill running. Furthermore, at the slowest velocities there was greater variability in metabolic cost per distance ($J \cdot kg^{-1} \cdot m^{-1}$). We believe

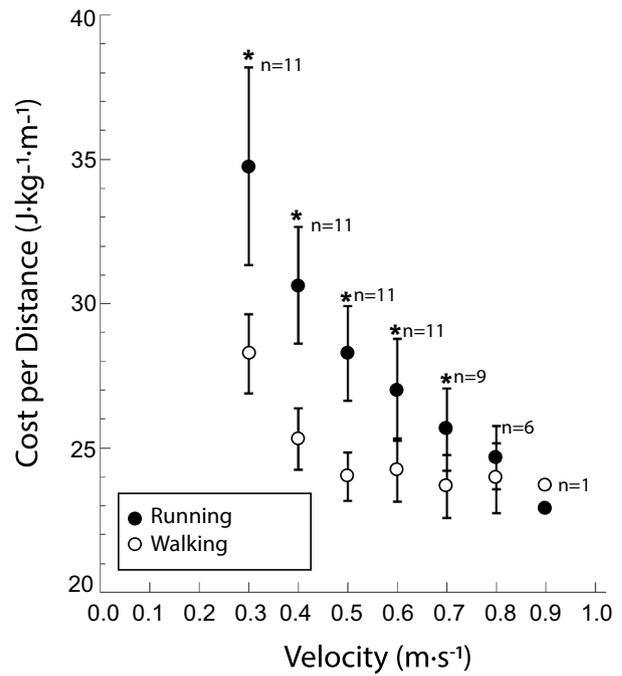


Fig. 3 Metabolic cost per distance ($J \cdot kg^{-1} \cdot m^{-1}$) for walking and running as a function of treadmill velocity (ms^{-1}) at 30° incline. Asterisks (*) indicate that there is a statistically significant difference between the metabolic cost of running and the metabolic cost of walking at that velocity ($p < 0.05$). Error bars show SD

that this reflects the fact subjects found such slow locomotion to be awkward.

Of course, when racing, the goal is to minimize time, not energy expenditure per distance. In an endurance race of 30–40-min duration, the athlete must stay below $\dot{V}O_{2max}$, even if it would hypothetically require less total energy to run faster. Daniels calculates that about 93% of $\dot{V}O_{2max}$ can be sustained for 30 min (Daniels and Gilbert 1979). Therefore, an elite VK racer should determine a velocity that allows them to stay at about 93% of their $\dot{V}O_{2max}$ while also minimizing energy cost as much as possible. Athletes who cannot finish a VK in 30 min must run at a lower percent of their $\dot{V}O_{2max}$. For example, a 45-min VK runner can sustain about 90% of $\dot{V}O_{2max}$. We have expanded on the competitive VK implications of our data in the “Appendix”.

Another purpose of this study was to develop a standardized steep uphill treadmill protocol for testing VK runners. We propose that this test be carried out on a 30° incline, since this is in middle of the range of “optimal” uphill angles at which both the metabolic power ($W \cdot kg^{-1}$) and energy cost per vertical distance ($J \cdot kg^{-1} \cdot m^{-1}$) is the least (Giovannelli et al. 2015). We encourage other investigators to use the same discontinuous testing protocol with the incline fixed at 30° and velocity increased by 0.1 ms^{-1} for each subsequent stage. Because of the linear relationship,

the exact velocity increment is not critical as long as comparisons are made at the same reference velocity. Although we did not test many elite athletes in this study, our data are a start to establishing normative values for this Colorado Vertical Kilometer Test (CVKT). We hope that this protocol will be used to test and compare VK runners around the world.

Limitations and future research

Our number of subjects ($n = 11$) and number of elite runners ($n = 1$) were limited. To determine if our results are applicable to specialist VK racers, future studies should expand the sample size using our protocol and include more elite VK runners. Another limitation was that our study was conducted on a treadmill with a smooth but high friction belt. In contrast, VK racecourses typically involve running on rocky, rugged and uneven terrain which is more energetically expensive (Voloshina and Ferris 2015; Zamparo et al. 1992). Thus, our results probably underestimate the actual metabolic power during VK racing.

Future studies should measure the metabolic effects of using poles or running while pushing on the thighs with one's hands. Both of these strategies are commonly used by VK racers, but it is unknown if they reduce metabolic power. Additionally, studies could use electromyography (EMG) to identify the relative activity of specific leg muscles during steep walking vs. steep running. Finally, future studies should seek to biomechanically differentiate walking from running at extreme slopes using both joint-level kinematic and kinetic analysis. In a previous study, we found that during steep uphill running, there is no aerial phase (Giovanelli et al. 2015). Furthermore, according to previous uphill studies, compared to level running, we would expect stride length to decrease and stride frequency to increase when running uphill (Gottschall and Kram 2005; Padulo et al. 2012). In the present study, we did not measure kinematic or biomechanical parameters, but subjects seemed able to intuitively distinguish between "walking" and "running", suggesting that there must be some subtle factor such as the primary muscle groups used that is different between the two gaits.

In summary, we measured the metabolic costs of walking and running on a 30° incline across a range of velocities. We found that at a 30° incline, metabolic power ($W\ kg^{-1}$) increases linearly with velocity. The metabolic power during walking is less than that for running at velocities between 0.3 and 0.7 ms^{-1} . However, the trends indicate that at faster velocities, running becomes cheaper. Additionally, we found that the metabolic cost per distance ($J\ kg^{-1}\ m^{-1}$) for both walking and running decreases at faster velocities, at least up to 0.9 ms^{-1} . Taken together, our data suggest that to maximize vertical ascent rate

and minimize metabolic power, slower VK racers should choose to walk, but faster racers should run.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights statement All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments.

Appendix

To mathematically predict a runner's VK time from their level 10-km time, we started using a runner's 10-km time to estimate their $\dot{V}O_{2\max}$. This was done in three steps. First, we calculated the runner's $\dot{V}O_{2\text{submax}}$ based on their average velocity during the 10-km race. The equation we used was from Daniels and Gilbert (1979) converted to velocity units of ms^{-1} . Throughout the appendix, $\dot{V}O_2$ is in units of $ml\ O_2\ kg^{-1}\ min^{-1}$, velocity (V) is in ms^{-1} , and time (t) is in minutes (Daniels and Gilbert 1979):

$$\dot{V}O_{2\text{submax}} \text{ on level ground} = 0.37 V^2 + 10.94 V - 4.6. \quad (4)$$

For example, using the world record 10-km time, 26.28 min with an average velocity of 6.34 ms^{-1} , we calculated that the runner's $\dot{V}O_{2\text{submax}}$ was 79.66 $ml\ O_2\ kg^{-1}\ min^{-1}$ during this race. Second, after calculating the runner's $\dot{V}O_{2\text{submax}}$, we used the runner's 10-km time to calculate the percent of $\dot{V}O_{2\max}$ that the runner could maintain when running their 10-km race (Daniels and Gilbert 1979):

$$\text{Sustainable\% of } \dot{V}O_{2\max} = 80 + 18.94393e^{(-0.013t)} + 29.9e^{(-0.19t)}. \quad (5)$$

For the 10-km world record holder, this percentage was 93.6%. Third, we used the calculated $\dot{V}O_{2\text{submax}}$ and calculated sustainable % of $\dot{V}O_{2\max}$ to calculate the runner's $\dot{V}O_{2\max}$. We did this using the following calculation:

$$\dot{V}O_{2\max} = \dot{V}O_{2\text{submax}} / (\text{sustainable\% of } \dot{V}O_{2\max} / 100). \quad (6)$$

For the world record holder, the calculated $\dot{V}O_{2\max}$ value was 85.0 $ml\ O_2\ kg^{-1}\ min^{-1}$. Once we had a $\dot{V}O_{2\max}$ value, we wanted to find the VK time which would require this same $\dot{V}O_{2\max}$. To do this, we started with a guess for their VK time. Using this time, we again went through the three-step process that was used for the level 10-km time. First, we inserted the VK runner's velocity into Eq. 7 which corresponds to the Eq. 1 presented earlier in the study to determine their $\dot{V}O_{2\text{submax}}$ at 30°:

$$\dot{V}O_2 \text{ submax at } 30^\circ = 50.329 V + 16.05. \quad (7)$$

Second, we again used Eq. 3 to determine the % of $\dot{V}O_{2max}$ that the runner could sustain during their VK race. Third, we inserted the $\dot{V}O_{2submax}$ at 30° and the sustainable % of $\dot{V}O_2$ into Eq. 4 to determine the $\dot{V}O_{2max}$.

Using these methods, we created a table of calculated $\dot{V}O_{2max}$ values based on level 10-km times and $\dot{V}O_{2max}$ values based on VK times. Finally, we matched each $\dot{V}O_{2max}$ based on a 10-km time to the same $\dot{V}O_{2max}$ based on a VK time. In this way, we determined the corresponding VK time for every 10-km time. Of course, this method assumes that $\dot{V}O_{2max}$ is the only determining factor for race time/performance, which is not completely correct. For complete accuracy, an individual's energy cost of running as well as their sustainable fraction of $\dot{V}O_{2max}$ should also be considered. Here, we assumed the same relationship between sustainable fraction of $\dot{V}O_{2max}$ vs. duration (i.e., Eq. 5) and that all runners have the same energy cost vs. velocity relationship (i.e., Eq. 4). Furthermore, this method uses the 30° $\dot{V}O_{2submax}$ equation (Eq. 7) from our paper, which was determined based on all of our data, even from speeds where not all runners could run/walk. However, it is still a good prediction tool for 10-km racers who would like to estimate their VK time.

Interestingly, we found through this process that the predicted VK time for the 10-km world record holder is 26.38 min, which is only 6 s slower than the level 10-km world record time, 26.28 min (Table 2). However, for slower 10-km runners, the predicted VK time was much slower than their level 10-km time (Fig. 4). For example, for a 40-min 10-km runner, the predicted VK time is 55:24, more than 15 min slower than the 10-km time. This is largely based on the differences in the runners' race duration and their sustainable % of $\dot{V}O_{2max}$ during their racing time. For example, on level ground, the 40-min 10-km runner runs at 4.16 ms⁻¹ and typically has a $\dot{V}O_{2submax}$ of 47.40 ml O₂ kg⁻¹ min⁻¹. To maintain the same $\dot{V}O_{2submax}$ up a 30° slope in a VK, the person could run at only 0.6 ms⁻¹. However, after 40 min, she would not have finished the race. To finish the VK she would need a longer duration (55 min), and hence, could only sustain 89% of her $\dot{V}O_{2max}$ as compared to 91% of $\dot{V}O_{2max}$ during the 10 k. However, based on our methods, faster runners would not experience as great of a difference in sustainable % of $\dot{V}O_{2max}$ for their 10 km and their VK. Consider the 26.28-min 10-k world record holder. His speed is 6.34 ms⁻¹ during a 10 k on level ground, making his $\dot{V}O_{2submax}$ about 79.66 ml O₂ kg⁻¹ min⁻¹. To run up the 30° slope and maintain the same $\dot{V}O_2$ as on level ground, he must run at 1.26 ms⁻¹. At this speed, he would be able to finish the VK in only 26.38 min. Because this race duration is short, the runner would be

Table 2 Level 10-km and equivalent VK running performance times

10 km (min)	VK (min:s)
26	25:54
27	27:30
28	29:12
29	30:54
30	32:42
31	34:36
32	36:30
33	38:36
34	40:48
35	42:54
36	45:11
37	47:30
38	50:03
39	52:36
40	55:24
41	58:12
42	61:12
43	64:24
44	67:42
45	71:24
46	74:54
47	78:30
48	82:54
49	87:24
50	91:36

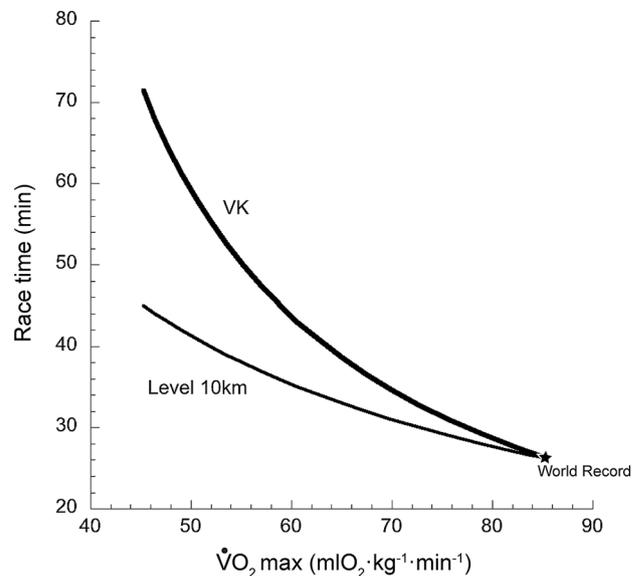


Fig. 4 Equivalent level 10-km and VK running performance times based on $\dot{V}O_{2max}$ (ml O₂ kg⁻¹ min⁻¹). See “Appendix” for calculations

able to maintain a high percentage of his $\dot{V}O_{2\max}$ during the race (93%). Thus, faster runners have less of a time difference between their level 10-km time and their predicted VK time because faster runners have less of a difference in their sustainable % of $\dot{V}O_{2\max}$ for the two races than slower runners do.

Energetically, these trends for the ratios can be understood by comparing $\dot{V}O_2$ vs. velocity equations for running up a 30° incline vs. running on the level. Our Eq. 7 for up a 30° incline has a slope of 50.329 ml O₂ kg⁻¹ min⁻¹ per ms⁻¹. If we convert the units of Leger and Mercier (1984) for level running, the slope is 11.387 ml O₂ kg⁻¹ min⁻¹ per ms⁻¹. Thus, to run a little faster uphill increases metabolic power much more than running a little faster on the level. More specifically, the world records for a flat 10-km race and a VK on a 30° incline (2 km of running distance) have a velocity ratio of ~5.0. The slopes of the $\dot{V}O_2$ vs. velocity equations have a ratio of 4.4. The y-intercept of Léger and Mercier (1984) is quite small but the y-intercept for a 30° incline is quite substantial (16 ml O₂ kg⁻¹ min⁻¹). For the 40-min flat 10-km runner, it comprises nearly 33% of their $\dot{V}O_{2\max}$. Overall, the divergence of the predicted VK race time vs. flat 10-km race time for slower runners is due to three factors: the extreme slope and intercept of the $\dot{V}O_{2\text{submax}}$ vs. velocity relationship and the reduced fraction of $\dot{V}O_{2\max}$ that can be sustained for the longer VK duration. The nearly identical flat 10 km and VK world records is not a coincidence but simply a mathematical reflection of the $\dot{V}O_2$ vs. velocity equations and the fact that the race distances are a ratio of 5 when the incline is a 30°.

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