

THE METABOLIC COSTS OF WALKING AND RUNNING UP A 30 DEGREE INCLINE;
IMPLICATIONS FOR VERTICAL KILOMETER FOOT RACES

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Chapter I

My motivation behind this thesis was to combine my two greatest passions: science and mountain running. I grew up in a mountain town with a mom who is an avid trail runner, so naturally, I became a trail runner as well. In addition to running, I love science. The inner-workings of the human body fascinate me. For this reason, I chose to explore the science behind running for my thesis.

My thesis consists of three chapters. In this first chapter, I briefly review the scientific literature on the exercise physiology and biomechanics of uphill running. My second chapter is a copy of an article published in 2016 in the *Journal of Applied Physiology*. For that study, I initiated the research and built a framework that allowed an existing treadmill to be inclined to 45 degrees, making it the world's steepest treadmill. After building the treadmill, I worked with a visiting doctoral student from Italy, Nicola Giovanelli, to further refine the treadmill and collect the data for the study presented in chapter II. The final chapter of my thesis comprises a manuscript describing an experiment that I conducted, analyzed and wrote almost exclusively on my own. I have submitted chapter III for peer-review and hopefully publication in the *European Journal of Applied Physiology*.

Uphill running biomechanics

Even if you aren't a runner, you've probably seen runners painfully straining at the end of a race. It's clear that running is an energetically demanding sport! While there is no doubt that track or road races, run mainly on level ground, are challenging, running uphill is far more so. The reason is that when running uphill, a runner must perform positive work, defined as force * displacement, to lift their body upwards against gravity. In the case of uphill running, the force is

the mass (M) of the runner multiplied by the Earth's gravitational acceleration ($g=9.81 \text{ m/s}^2$).

The height that the weight must be raised is calculated from the product of the distance run and the sine of the angle (θ) of the running slope. Mathematically the equation is $\text{Work} = M \cdot g \cdot h \cdot \sin \theta$. So, as the angle of the running slope gets larger (the slope gets steeper), the sine of that angle gets larger, making the work performed by the runner greater. Because running uphill requires more work than running on level ground, it also requires a greater amount of mechanical power. Mechanical power is defined as the work done per unit time, and the mechanical power required to lift the mass of the body can be calculated by multiplying the force of gravity by the vertical running velocity ($P=W \cdot V_{\text{vert}}$). Thus, as velocity increases, so does mechanical power.

Due to the differences in work and mechanical power for level running and uphill running, the biomechanics of the two activities are slightly different at the joint and muscle levels. After running on the level, uphill and then downhill runners will often claim that they “used different muscles” in the three conditions. In 1997, Sloniger et al. investigated that intuitive idea using the latest biomedical technology. They conducted two studies comparing lower extremity muscle activation during level and uphill (10% grade) running to exhaustion. Using proton magnetic resonance (pNMR) images, Sloniger et al. was able to visualize contrast shifts which indicate how much ATP is being consumed by specific muscles during running. In that way, they were able to quantify which muscles were active as well as each muscle's degree of activity. In the Sloniger et al. studies, 12 female runners ran to exhaustion (a time period of ~2-3 minutes) on a 0% grade and a 10% grade. By comparing pNMR images taken before and after each bout of exercise, Sloniger et al. determined that running uphill activates a greater percentage of lower extremity muscle mass than level running does. Additionally, they found

that this increase in volume of muscle activated was not caused by increased use of the same muscles, but instead was indeed caused by use of additional different muscles. For example, running uphill activated lower leg muscles, such as the soleus, far more than level running did. Interestingly, even when running to exhaustion, the lower limb muscles were not activated 100%. That finding may indicate that there is a neural limit on motor recruitment, preventing the body from increasing muscle mass recruitment past a certain threshold.

As I described earlier, when running uphill, there is an increase in net mechanical work to increase the potential energy of the body. But which muscles and joints are primarily involved in producing that extra work? The ankle muscles? The quadriceps acting at the knee? Or the large gluteal muscles acting to extend the hips? Roberts et al. (2005) addressed those questions by measuring joint kinematics and ground reaction forces while subjects ran at various inclines (0° , 6° , and 12°). They determined that it is primarily the hip joint (and thus the gluteus maximus muscles) that increases torque output (net joint moment). In comparison, the knee and the ankle joint function did not significantly increase when running up inclines.

Another biomechanical factor which changes during incline running is the use of elastic energy. During level running, elastic energy is stored in the tendons and almost all of it can be recovered (Snyder et al., 2012). Thus during one step, the combined mechanical energy of the body ($E_{\text{com}} = \text{Gravitational Potential Energy} + \text{Kinetic Energy}$) decreases during the first half of the step, and increases during the second half of the step. Overall, there is no net change in E_{com} . However, this is not the case for uphill running. Snyder et al. determined that when running up inclines (3° , 6° , and 9°) rather than having no net change in mechanical energy, E_{com} increased over the course of a step. Thus, in each step, energy other than just stored elastic energy must have contributed to the increase in energy. This is because when running up steep slopes, the

body has to generate net positive energy to raise the center of mass as well as make up for the fact that at steeper inclines, the maximum amount of elastic energy that can be stored is diminished. The increase in positive mechanical energy generated by the body when running uphill is the main reason for the increase in metabolic energy cost of running on uphill slopes as compared to level surfaces.

Exercise Physiology

To understand the interaction between the biomechanics and energetics of running in general, it is necessary to have a basic understanding of the physiology of exercise. There are two main ways that exercise physiologists assess a runner's ability: $\dot{V}O_2$ max and economy.

In everyday activities, the body takes in oxygen which is used to aerobically produce ATP, the form of energy used within the body. As would be expected, when exercising, the amount of ATP, and thus the amount of oxygen, required by the body increases. The maximum amount of oxygen that a person can take up and use to meet the aerobic energetic demands is called the $\dot{V}O_2$ max. $\dot{V}O_2$ max ($\text{mlO}_2/\text{kg}/\text{min}$) can vary greatly between people (i.e. couch potatoes vs. endurance athletes) and is a fairly good predictor of aerobic running performance. Runners who can take up larger amounts of oxygen, can then produce more ATP, allowing them to maintain a challenging running pace for longer than those with a small $\dot{V}O_2$ max (Foster et al., 1978). To some extent, a high $\dot{V}O_2$ max is a factor which can be developed. For example, if untrained individuals start a running program, they can improve their $\dot{V}O_2$ max (Daniels et al., 1978). On the other hand, for trained individuals, $\dot{V}O_2$ max is relatively stable, meaning that each runner has a limit beyond which $\dot{V}O_2$ max can no longer be increased (Daniels et al., 1978). However, even once this $\dot{V}O_2$ max limit is reached, trained individuals can continue to improve

their running performance, indicating that $\dot{V}O_2$ max is not the only factor that determines running ability.

Another contributing factor to a runner's ability is running economy. Running economy is defined as the rate of oxygen uptake of an individual running at a standardized velocity (Conley et al., 1980). Those that take up less oxygen when running at a certain speed are considered "more economical" than others. Essentially, because oxygen uptake is directly related to ATP production, economical runners are good at conserving energy, so they can run at fast paces at a lower energetic cost than un-economical runners can. As with $\dot{V}O_2$ max, running economy can be improved; trained runners are generally more economical than untrained runners (Morgan et al. 1995). Although being economical allows runners to save energy, ultimately, the ideal runner would have both a high $\dot{V}O_2$ max and excellent economy.

Level walking and running energetics

The energetics of locomotion on level ground are well studied. When running on level ground, the energetic cost increases almost linearly with a runner's velocity. As an athlete runs more quickly, the metabolic rate (= energy cost per unit time) is greater (Margaria et al. 1963; Di Prampero et al. 1986). As a result, the cost of running a given distance is nearly independent of running speed. On the other hand, the energetic cost of walking a given distance reaches a minimum at an optimum speed (~1.3 m/s), and costs more when going either slower or faster than optimal (Minetti et al., 2002; Di Prampero et al., 1986; Margaria et al., 1963). Once level running energetics were well established, scientists started to ask, "how do the energetics change when the trail heads uphill?"

Uphill running energetics

Two of the earliest studies on the energetics uphill locomotion were conducted by Rudolfo Margaria et al. in 1938 and 1963. In those studies, he investigated the cost of uphill running as compared to level running at inclines ranging from -20% to +15%. He found that the energetic cost (metabolic rate) of running increased linearly with incline. However, at each slope, the net energy cost of running a defined distance was independent of the velocity. So, for example, the energy required to run 1 km at a 10% grade was the same, regardless of the running velocity.

Additionally, Margaria et al. introduced the concept of mechanical efficiency in the context of uphill running. He defined mechanical efficiency as the ratio of mechanical power (= the mass of the runner * gravity * velocity * sin (angle of the running slope)) to the metabolic power consumption of an individual. Interestingly, in the 1963 study, Margaria et al. found that trained athletes were only about ~5-7% more efficient than non-athletes. This finding suggests that efficiency is not the reason that trained runners perform better than untrained individuals. Rather, Margaria et al. suggested that trained individuals probably have a greater capacity for oxygen uptake ($\dot{V}O_{2max}$) than those who are untrained. For all runners, Margaria et al. predicted that mechanical efficiency on inclines above +20% would be about 25%, which is the efficiency of purely concentric muscle contractions.

In 2002, Minetti et al. extended Margaria et al.'s findings to more extreme inclines, ranging from -45% to +45%. However, many of the results were similar. Minetti et al. determined that at a given incline, oxygen uptake increased linearly with running velocity. Furthermore, like Margaria et al. 1963, Minetti et al. found that at steeper uphill gradients,

oxygen uptake and the cost of running also increased. Confirming Margaria et al.'s hypothesis that mechanical efficiency would be ~25% when running up steep inclines, Minetti et al. found that above a 15% grade, mechanical efficiency ranged from 22-24%.

Although Minetti et al.'s (2002) results were important for steep uphill running, they were not necessarily applicable to less steep uphill inclines. Thus, in 2014, Hoogkamer et al. created a model for the energetics of uphill running between 0 and 9 degrees (~0-15.8%). According to Hoogkamer et al.'s theory, the cost of uphill running cannot accurately be found by simply adding the cost of horizontal running to the cost of lifting one's mass against gravity. Instead, he proposed that three key factors determined the energy cost of uphill running. Hoogkamer's first factor is the energy cost of bouncing perpendicularly to the running surface, which remains constant between level and uphill running. Second, Hoogkamer et al. delineated the amount of energy used to brake and propel the body parallel to the running surface. As incline increases, although there is more lifting vertically, there is less braking and propulsion, so this factor actually decreases during uphill running. However, the third factor, the cost of lifting one's mass against gravity begins to dominate on steep inclines. Hoogkamer et al. showed that together these factors could be combined and accurately estimate the cost of uphill running between 0 and 9 degrees.

Following Hoogkamer et al.'s study, in just the last few years, there have been multiple studies investigating ways to enhance and assess uphill running performance. In 2016, Balducci et al. compared the maximal oxygen uptake ($\dot{V}O_{2max}$) and cost of running (C_r) of elite mountain runners on a treadmill at 0%, 12.5% and 25% grades. Many scientists use tests, such as $\dot{V}O_{2max}$ tests, to predict running performance. However, these tests were originally designed for track and road runners. Thus, the aim of their study was to determine if uphill running performance,

like level running performance, can be predicted using level running tests. Balducci et al. found that at each incline tested (0%, 12.5% or 25%), the runners' HRmax and $\dot{V}O_{2max}$ were the same. Thus, indicating that tests for these two parameters can be carried out at any treadmill grade and will yield the same results. In other words, a runner's uphill HRmax and $\dot{V}O_{2max}$ are the same as his/her level HRmax and $\dot{V}O_{2max}$. Furthermore, as would be expected from previous studies, the cost of running a given distance, C_r , increased with increasing slope (Margaria et al., 1963; Minetti et al., 2002). Yet, interestingly, Balducci et al. found that the increase in C_r between slopes varied greatly from one runner to the next. In other words, some subjects had a much lower cost of uphill running than others. Thus, unlike HRmax or $\dot{V}O_{2max}$, uphill C_r cannot be predicted based on level C_r . Instead, to determine uphill C_r , runners should be tested on an incline. Then, uphill C_r may be used to predict uphill racing performance; those with lower uphill C_r may be more successful than those with higher uphill C_r . Balducci et al. measured various parameters such as stride frequency, stride length, and body mass index, but none of these were correlated with a runner's uphill C_r . Therefore, it is still unknown why some runners have a greater increase from level C_r to uphill C_r than others.

With the studies reviewed in this chapter, I have set the stage for the study presented in chapter II (Giovanelli et al. 2016). In particular, Giovanelli et al. was geared towards Vertical Kilometer (VK) races, which gain 1000 m of elevation over a course length of less than 5000 m (International Skyrunning Federation: <http://www.skyrunning.com>). Because these races are generally run on very steep inclines, the aim of the study was to determine the metabolic cost of running and walking at extreme slopes.

Chapter II

Energetics of vertical kilometer foot races; is steeper cheaper?

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RUNNING HEAD: energetics of uphill running

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ABSTRACT

Vertical kilometer foot races consist of a 1,000 m elevation gain in less than 5,000 m of overall distance and the inclines of the fastest courses are $\sim 30^\circ$. Previous uphill locomotion studies have focused on much shallower angles. We aimed to quantify the metabolic costs of walking and running on very steep angles and to biomechanically distinguish walking from running. Fifteen runners (10 M, 5 F, 32.9 ± 7.5 years, 1.75 ± 0.09 m, 64.3 ± 9.1 kg) walked and ran for 5 minutes at 7 different angles (9.4° , 15.8° , 20.4° , 24.8° , 30.0° , 35.0° and 39.2°) all at a fixed vertical velocity (0.35 m/s). We measured the metabolic rates and calculated the vertical costs of walking ($C_{w_{\text{vert}}}$) and running ($C_{r_{\text{vert}}}$). Using video analysis, we determined stride frequency, stride length and duty factor (fraction of stride that each foot is in ground contact). At all angles other than 9.4° , $C_{w_{\text{vert}}}$ was cheaper than $C_{r_{\text{vert}}}$ (average $-8.45\% \pm 1.05\%$; $p < 0.001$). Further, broad minima for both $C_{w_{\text{vert}}}$ and $C_{r_{\text{vert}}}$ existed between 20.4° and 35° (average $C_{w_{\text{vert}}}$ $44.17 \pm 0.41 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ and average $C_{r_{\text{vert}}}$ $48.46 \pm 0.35 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$). At all angles and speeds tested, both walking and running involved having at least one foot on the ground at all times. But, in walking, stride frequency and stride length were $\sim 28\%$ slower and longer, respectively than in running. In conclusion, we found that there is a range of angles for which energy expenditure is minimized. At the vertical velocity tested, on inclines steeper than 15.8° , athletes can reduce their energy expenditure by walking rather than running.

Keywords: walking, running, uphill, cost of transport

INTRODUCTION

In vertical kilometer foot races (VK), athletes complete a course with 1,000 m vertical elevation increase in less than 5,000 m of total race length (International Skyrunning Federation rules <http://www.skyrunning.com>). Terrain, slope and length vary between racecourses. To date, the world record for men in the VK is 29 minutes and 42 seconds, set on a course with a length of 1,920 m, an average inclination of 27.5° (Km vertical de Fully, Switzerland). That equates to an average vertical velocity of ~ 0.56 m/s and an average velocity parallel to the ground of 1.21 m/s. A VK course with only a slight incline would require an unreasonably fast parallel velocity. For instance, a racecourse with an incline of only 1° would require the impossible running speed of 31.84 m/s to rise 1,000 m in 30 minutes. Conversely, a course with a gradient of 40° would require a speed of only 1.03 m/s to gain 1,000 m in 30 minutes. But, if the course is too steep, the rock-climbing techniques required would likely be slower than walking/running at more moderate slopes. Analysis of the best performances in different VK races suggests that there may be an optimal angle for achieving the best time (Figure 1). Since there are no VK races with an average incline steeper than 28.9° (La Verticale du Grand Serre, France), it is unknown if the optimal gradient is actually steeper.

Another factor to consider is that in VK races, some athletes walk, some run and some alternate gaits. It is not clear which gait or combination is optimal. On level ground or treadmills, at matched speeds slower than ~ 2.0 m/s, walking requires less metabolic energy than running (3, 15, 17, 25). This is generally attributed to the more effective inverted pendulum-like exchange of mechanical energy at slower walking speeds and the superior elastic energy storage and recovery of running at faster speeds (6). However, on uphill grades both of those mechanisms are

disabled (8, 24). On the level (17) as well as moderate inclines and declines (18, 19) the preferred walk-run transition speed occurs near but not exactly at the metabolically optimal transition speed. As speed is increased, people typically first adopt a running gait at a speed slightly slower than the metabolic crossover point.

The metabolic cost of uphill walking and running has long been of interest to exercise physiologists (3, 14, 15, 18) but almost all studies have examined uphill walking or running on angles less than 9° . One highly relevant exception is the innovative study by Minetti et al. (21). They measured the metabolic cost ($J \cdot kg^{-1} \cdot m^{-1}$) of walking (C_w) and running (C_r) on a range of slopes up to 24.2° . Note, for C_w and C_r , the calculated distance is parallel to the surface or treadmill. They concluded that at a given treadmill belt speed, C_w and C_r are directly proportional to the slope above $+15\%$ (8.5°) and that C_w and C_r converge at steeper angles. Minetti et al. (21) also defined the vertical costs of walking ($C_{w_{vert}}$) and running ($C_{r_{vert}}$), as the energy expended to ascend one meter vertically. $C_{w_{vert}}$ and $C_{r_{vert}}$ both decreased at steeper angles reaching minimum values at slopes ranging from 20% (11.3°) to 40% (21.8°). However, we are reluctant to extrapolate from the data of Minetti et al. to the steeper slopes at which VK races are often contested. Further, VK competitors often alternate between walking and running at the same speed and Minetti et al. did not directly compare the energetics of the two gaits at matched speeds. Finally, it is not clear if the traditional biomechanical distinction between walking and running on level ground (i.e. in running, the center of mass trajectory reaches its lowest point at mid-stance and there is an aerial phase when no feet are in contact with the ground) applies on very steep slopes. Previous investigators have used the terms “Groucho

running” (16) and “grounded running” (23) to describe a bouncing gait that does not involve an aerial phase.

To the best of our knowledge, there are no prior scientific studies of human walking or running at the steep angles that are encountered in the fastest VK races. Minetti et al. (20) analyzed stair running races but such “skyscraper races” are much shorter duration than VK (from 50 s to about 14 min compared with ~30 min) and they did not measure the metabolic cost. Intriguingly, Kay’s mathematical analysis of uphill mountain running races (12) concluded that if an optimum gradient for ascent exists, it is steeper than the range of gradients studied so far.

The primary purpose of this study was to quantify the metabolic costs of walking and running across a wide range of inclines up to and beyond those used in VK races. We aimed to determine if walking or running is more economical and if there are energetically optimal angles for the two gaits. Specifically, we compared walking and running at a fixed vertical velocity (0.35 m/s) at angles ranging from ~10 to ~40°. Based on the findings of Minetti et al. (21), and because the treadmill belt speeds we studied are < 2.0 m/s, we hypothesized that: 1. walking would require less metabolic energy than running. We further hypothesized that: 2. for both walking and running, there would be distinct intermediate angles (~30°) that minimize the energetic cost of ascending at a fixed vertical velocity.

Our secondary purpose was to distinguish the biomechanics of walking vs. running on steep inclines. We hypothesized that: 3. at steep angles and slow treadmill belt speeds, running would

not involve an aerial phase. However, a greater stride frequency during running would distinguish it from walking.

MATERIALS AND METHODS

Subjects. Fifteen healthy, competitive mountain runners (10 males, 5 females, 32.9 ± 7.5 years, 1.75 ± 0.09 m, 64.3 ± 9.1 kg) volunteered and provided informed consent as per the University of Colorado Institutional Review Board.

Experimental design.

We modified a custom treadmill so that it was inclinable from 0 to 45° (Figure 2). To provide adequate traction, we adhered a wide swath of skateboard grip tape (i.e. sandpaper) to the treadmill belt (Vicious Tape, Vancouver, BC Canada). To protect the electronic motor controller, we mounted three v-belt pulleys on the treadmill drive roller, hung ropes over the pulleys and attached moderate weights to the ropes (~8 kg). We chose the minimum amount of weight such that when the subject stood on the belt with the motor turned off, the belt did not move. Providing a mechanical resistance to the motor allowed it to produce power and maintain a nearly constant treadmill belt speed.

The study consisted of three sessions. During the first session (familiarization), each athlete walked and ran for 2 to 3 minutes on the treadmill at 4 angles (9.4, 30.0, 35.0 and 39.2°). During the second and third visits, subjects either walked (e.g. Day 2) or ran (e.g. Day 3) for 5 minutes at 7 different angles (9.4°, 15.8°, 20.4°, 24.8°, 30.0°, 35.0° and 39.2°) and corresponding treadmill belt speeds (2.14, 1.29, 1.00, 0.83, 0.70, 0.61, 0.51 m/s). Subjects had five minutes rest

between trials. Half of the subjects walked on Day 2 and ran on Day 3; the other half did the opposite. These angle and speed combinations fixed the vertical velocity at 0.35 m/s. We chose this vertical velocity knowing the VK records for men (29:42 = 0.56 m/s vertical velocity) and women (36:04 = 0.46 m/s vertical velocity) and recognizing the need for submaximal intensities so that we could record steady-state metabolic rates. Pilot testing indicated that faster vertical velocities would elicit non-oxidative metabolism. For each subject, we randomized the order of the angles used on both Days 2 and 3.

Metabolic data. To determine the metabolic rates during walking and running, we used an open-circuit expired gas analysis system (TrueOne 2400, ParvoMedic, Sandy, UT, USA). Subjects wore a mouthpiece and a nose clip allowing us to collect the expired air determine measure the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$). We averaged the data of the last 2 minutes of each trial. We then calculated metabolic rate in W/kg using the Brockway equation (2). We only included trials with respiratory exchange ratios (RER) less than 1.0. We calculated the vertical costs ($J \cdot kg^{-1} \cdot m^{-1}$) of walking ($C_{w_{vert}}$) and running ($C_{r_{vert}}$) by dividing the gross metabolic power by the vertical velocity.

Biomechanical parameters. To measure stride parameters, we recorded each trial using a high-speed video camera (Casio EX-FH20) at 210 fps. We extracted contact and stride times for 10 strides using Kinovea 0.8.15 software (www.kinovea.org) and then calculated stride frequency ($=1/\text{stride time}$) and stride length ($=\text{velocity}/\text{stride frequency}$). To determine duty factor, we divided contact time for one foot by the total stride period.

Statistical analysis

We analyzed the data using SPSS with significance set at $p \leq 0.05$. We analyzed the vertical cost of walking ($C_{w_{\text{vert}}}$), vertical cost of running ($C_{r_{\text{vert}}}$) and biomechanical parameters with a general linear model repeated measures considering two factors (slope and gait: walking versus running). We followed up with a Bonferroni post-hoc test when significant differences were detected. At 9.4° the treadmill belt speed was faster than the walk-run transition speed, thus only 9 subjects were able to complete the entire 5-minute trial using a walking gait. Therefore, when making statistical comparisons of the 9.4° trials, we calculated the variables for just those 9 subjects.

RESULTS

Vertical cost of walking vs. running. At 9.4° , the vertical cost of walking ($C_{w_{\text{vert}}}$) was numerically slightly greater than vertical cost of running ($C_{r_{\text{vert}}}$) but they were not statistically different ($n=9$; $+1.54\%$; $p=0.545$). However, $C_{w_{\text{vert}}}$ was significantly less than $C_{r_{\text{vert}}}$ at 15.8° (-6.35% ; $p=0.001$), 20.4° (-8.45% ; $p=0.001$), 24.8° (-8.73% ; $p=0.001$), 30.0° (-9.23% ; $p=0.001$), 35.0° (-8.99% ; $p=0.001$) and 39.2° (-8.93% ; $p=0.001$) (Table 1).

$C_{w_{\text{vert}}}$ was numerically least at 30° ($43.86 \pm 2.02 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$), but was not statistically distinguishable from 20.4° ($44.23 \pm 1.69 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$), 24.8° ($44.10 \pm 2.10 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) or 35.0° ($44.57 \pm 2.14 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) (Table 1, Figure 3). $C_{w_{\text{vert}}}$ at 15.8° was less than $C_{w_{\text{vert}}}$ at 9.4° ($n=9$; -18.2% ; $p=0.001$). Further, $C_{w_{\text{vert}}}$ at 20.4° , 24.8° , 30.0° and 35.0° was less than $C_{w_{\text{vert}}}$ at 15.8° (average -5.47% ; $p < 0.001$). Additionally, $C_{w_{\text{vert}}}$ at 39.2° was significantly greater than $C_{w_{\text{vert}}}$ at 20.4° , 24.8° , 30.0° and 35.0° (average $+4.31\%$; $p < 0.001$).

Cr_{vert} was numerically least at 24.8° ($48.22 \pm 2.57 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$), but was not statistically distinguishable from at 20.4° ($48.31 \pm 2.54 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$), 30.0° ($48.32 \pm 3.07 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) or 35.0° ($48.97 \pm 3.01 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$) (Table 1, Figure 3). Cr_{vert} at 15.8° was less than Cr_{vert} at 9.4° (-7.88%; $p=0.001$). As was true for walking, Cr_{vert} at 20.4° , 24.8° , 30.0° and 35.0° was less than Cr_{vert} at 15.8° (average -2.90%; $p<0.001$). Finally, Cr_{vert} at 39.2° was greater than Cr_{vert} at 20.4° , 24.8° , 30.0° and 35.0° (average +4.42%; $p<0.001$).

Biomechanical parameters. Walking stride frequency was slower than running stride frequency at every incline (average $-27.99\% \pm 7.75\%$; $p<0.001$) (Figure 4A). Thus, walking stride length was longer than running stride length at every incline (Figure 4B). In both walking and running, stride frequency and stride length decreased on steeper inclines at the correspondingly slower treadmill belt speeds (Figure 4A and 4B). Duty factor was greater than 50% for both walking and running conditions at all speed/incline combinations tested, indicating non-aerial gaits. Walking duty factor was greater than the running duty factor at every incline (average $10.29 \pm 5.92\%$; $p<0.001$) except at 40° .

DISCUSSION

Our major findings are: 1) across the range of angles and speeds tested, which fixed the vertical velocity, walking is less expensive than running, 2) there is a broad range of angles for which the vertical costs of walking and running are minimized, 3) at the angle/speed combinations we studied, in both walking and running, at least one foot is always in contact with the ground.

Our results support the hypothesis that at a fixed vertical velocity of 0.35 m/s, walking would be less expensive than running at steep inclines, though at 9.4° there was not a significant difference between gaits. Explaining the energetic difference between walking and running is not straightforward. We know that the inverted pendulum and spring mechanisms that conserve mechanical energy during level walking and running respectively are disabled during uphill locomotion (8, 24), but it is not yet possible to quantify those effects. Minetti et al. (18) showed that during uphill locomotion the “internal work” for reciprocating the limbs is actually greater in walking than in running despite the slower stride frequencies in walking. Kram and Taylor (13) established that metabolic rate is inversely proportional to contact time during level running. At the inclines and speeds in the present study, the contact times for running averaged $34.4 \pm 3.2\%$ less than for walking and that may at least partially explain the metabolic cost difference between the two gaits. Further, because of how the legs are positioned differently in the two gaits, the mechanical advantages of the extensor muscles at the knee are larger in level walking vs. running (1). Smaller muscle forces require a smaller active muscle volume which is energetically cheaper. However, we are not aware of any mechanical advantage measurements for steep uphill locomotion.

At 9.4°, the treadmill belt speed (2.14 m/s) was much faster than during the other trials, and is equal to the spontaneous walk-run transition speed on level ground, ~2 m/s (3, 11, 15). Previous studies (4, 10, 11) have demonstrated that the preferred transition speed is slower on moderate inclines and that humans generally choose the gait that minimizes their metabolic cost (17). In the present study, at 9.4° and 2.14 m/s, all of the subjects informally expressed that they would prefer to run. At 15.8° and 1.29 m/s, walking was significantly cheaper but most of the subjects

expressed that they would prefer to run. Between 20.4° and 1.00 m/s and 30.0° and 0.70 m/s subjects mentioned that walking felt better. But, if there were no constraints, they thought that they would prefer to alternate between the two gaits every one or two minutes. At 35.0° and 0.61 m/s and 39.2° and only 0.51 m/s, gait preference was ambiguous. Subjects expressed that they did not strongly prefer walking (the less expensive gait) because they felt running involved less musculoskeletal “stress” and also balance was more challenging when walking. A future study focused on gait preference, metabolic cost and perceived effort during both walking and running on steep inclines is needed to better understand this topic.

We reject our second hypothesis. Rather than there being a distinct optimum, we found that there is a range of angles for which $C_{w_{vert}}$ and $C_{r_{vert}}$ are minimized. For both walking and running, the minimum values were reached between 20.4° and 35°. A second order polynomial regression suggests that the minimum values for $C_{w_{vert}}$ and $C_{r_{vert}}$ would be attained at 28.4° ($R^2=0.64$) and 27.0° ($R^2=0.33$), respectively. At angles shallower than 20°, both $C_{w_{vert}}$ and $C_{r_{vert}}$ are significantly greater. This could be due in part to the greater metabolic power required to support body weight at faster treadmill belt speeds (9). Further, at our extreme angle, 39.2° there was an increase in $C_{w_{vert}}$ and $C_{r_{vert}}$ which we believe is caused by the difficulty of maintaining balance at such steep angles. Part of the balance challenge was due to the fact that at 39.2°, the treadmill belt speed was only 0.55 m/s and involved exaggerated contact times (0.924 ± 0.09 s for walking and 0.588 ± 0.11 s for running). In a pilot study, two subjects tried to walk and run with the treadmill inclined to 45° and the $C_{w_{vert}}$ and $C_{r_{vert}}$ both increased dramatically compared to ~40°. Balance was quite difficult for those pilot subjects and they frequently grabbed the handrails. Moreover, at that extreme slope, both subjects reported discomfort in their calves and feet

because of excessive stretch. For that reason, we “only” studied up to 39.2° in the actual experiment. For C_w and C_r at angles between 10° and 24.8° , our results are congruent with the 5th order polynomial regression formula given by Minetti et al. (21). However, extrapolating beyond 24.8° , that formula leads to large overestimates of the C_w and C_r (Figure 5).

A recent paper from our lab, Hoogkamer et al. (9), proposed a new explanation for the metabolic cost of running up relatively shallow inclines $< 9^\circ$. In that model, the cost of running (C_r) is determined by three factors: the cost of perpendicular bouncing, the cost of parallel braking and propulsion and the cost of lifting the center of mass. They assumed a constant efficiency for performing the center of mass lifting work, their results supported that assumption and they derived a value of ~29% efficiency. In the present study, the vertical work rate was held constant between the different inclines and thus with the same efficiency the vertical cost would be the same between running conditions. In the Hoogkamer et al. study, as the incline approached 9° , the cost of parallel braking and propulsion approached zero. At the even steeper angles used in the present study, the cost of parallel braking and propulsion (the “wasted impulse”) presumably is nil. Finally, Hoogkamer et al. reasoned that the cost of perpendicular bouncing would not change over the moderate inclines they studied. At the steeper inclines used in the present study, just based on trigonometry, the perpendicular forces would be less than during level running (e.g. ~13% reduced on a 30° incline, $\cosine = 0.866$). However, the running speeds on the inclines studied here were much slower than typical level running speeds and involved prolonged contact times. Prolonged contact times presumably would allow recruitment of slower (and more economical) muscle fibers to generate the perpendicular forces, but long contact times impair the spring-like bouncing motion and therefore might be less economical (5). Overall, from the

Hoogkamer et al. perspective, the broad plateau of Cr_{vert} observed for running at angles from 20.4° to 35° probably results from counteracting savings vs. costs for perpendicular bouncing at the different speed and angle combinations. A similar model for uphill walking has not yet been put forth.

As we hypothesized, there was no aerial phase in steep uphill running, i.e. the duty factor (average $62.7 \pm 0.80\%$) was greater than 50% at every incline tested. This suggests that other parameters should be considered to distinguish between walking and running uphill. McMahon et al. (16) defined “Groucho running” as a non-aerial gait that still involved a bouncing center of mass trajectory, i.e. the center of mass was lowest at mid-stance. Rubenson et al. (23) used the term “grounded running” for the same phenomenon in running birds. Because our subjects were running uphill, the center of mass-based definition probably does not apply (8). Nonetheless, when we asked our subjects to either “walk” or “run”, they all subjects immediately and intuitively distinguished the two gaits. Previous studies reported that when treadmill speed is fixed, on steeper inclines, stride length and aerial time decrease and stride frequency increases (7, 22). We observed decreases in both stride frequency and stride length at steeper angles (figure 4 and 5) because treadmill speed was slower at the steeper angles we tested. Thus, with our experimental design, we could not determine how speed and incline independently affect stride frequency and stride length.

Limitations and future research

One limitation of our study is that it was conducted on a treadmill whereas VK races are performed on uneven terrain (ski slopes, trails) with the presence of stones, stairs, gravel etc.

Voloshina and Ferris report that the energy expenditure of running on an uneven terrain treadmill was only 5% higher than on a smooth treadmill (26). But, Zamparo et al. showed that running on a sandy terrain requires 20% more energy than on firm terrain (27). Thus, the cost of transport during a real VK race is surely somewhat greater than what we measured on our treadmill.

Another limitation was that our treadmill did not permit the use of poles. The VK world record as well as most of the fastest performances outdoors were achieved using poles.

Future studies should compare uphill walking and running with and without poles in order to determine if using poles is advantageous. Further studies involving different combinations of vertical velocity, treadmill speed and angle are also needed. Finally, a more thorough biomechanical comparison of walking vs. running is in order since on steep inclines the defining characteristic(s) of these two gaits are not yet clear.

In conclusion, we studied the cost of walking and running at angles substantially steeper than any previous study. We found that for both walking and running there is a range of angles (20.4 degrees to 35.0 degrees) for which energy expenditure is minimized. Our data suggest that, to achieve the best results, VK races should be contested within this range of angles. Although other factors may be important, on very steep slopes, athletes can reduce their energy expenditure by walking rather than running.

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GRANTS

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TABLES AND FIGURES

TABLE 1. The Vertical cost of walking and running as a function of the slope angle

Angle, °	Treadmill Belt Speed, m/s	Walk, J/kg·m	Run, J/kg·m	Difference, %	P
9.4	2.14	55.67 ± 3.80	54.83 ± 2.29	1.53	0.545
15.8	1.29	46.73 ± 2.19	49.90 ± 2.37	-6.35	0.001
20.4	1.00	44.23 ± 1.69	48.31 ± 2.54	-8.45	0.001
24.8	0.83	44.01 ± 2.10	48.22 ± 2.57	-8.73	0.001
30.0	0.70	43.86 ± 2.02	48.32 ± 3.07	-9.23	0.001
35.0	0.61	44.57 ± 2.14	48.97 ± 3.01	-8.99	0.001
39.2	0.55	46.07 ± 2.49	50.59 ± 3.70	-8.93	0.001

Vertical cost of walking and running (mean±SD, in J/kg·m) as a function of the slope angle (°) and treadmill belt speed (m/s). Vertical velocity was fixed at 0.35 m/s. At 9.4° only 9 subjects were able to walk at the required speed (2.14 m/s). For all other angles n=15.

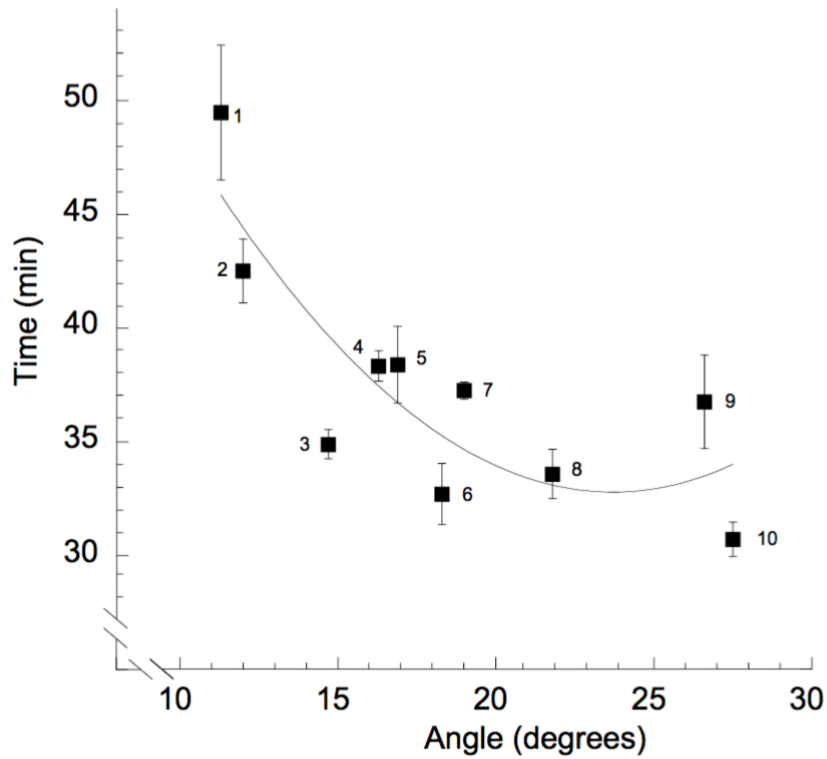


Figure 1. The average of the five best performances for ten different VK races in the year that the each course record was set. 1: The Rut VK (USA); 2: Val Resia VK (I); 3: Mont Blanc VK (F); 4: Limone Vertical Extreme (I); 5: Latemar VK (I); 6: VK Lagunc (I); 7: VK face de Belvedere (F); 8: Dolomites VK (I); 9: VK Col de Lana (I); 10: VK de Foully (CH); 11: La Verticale du Grand Serre (F); USA: United State of America; I: Italy; F: France; CH: Switzerland.

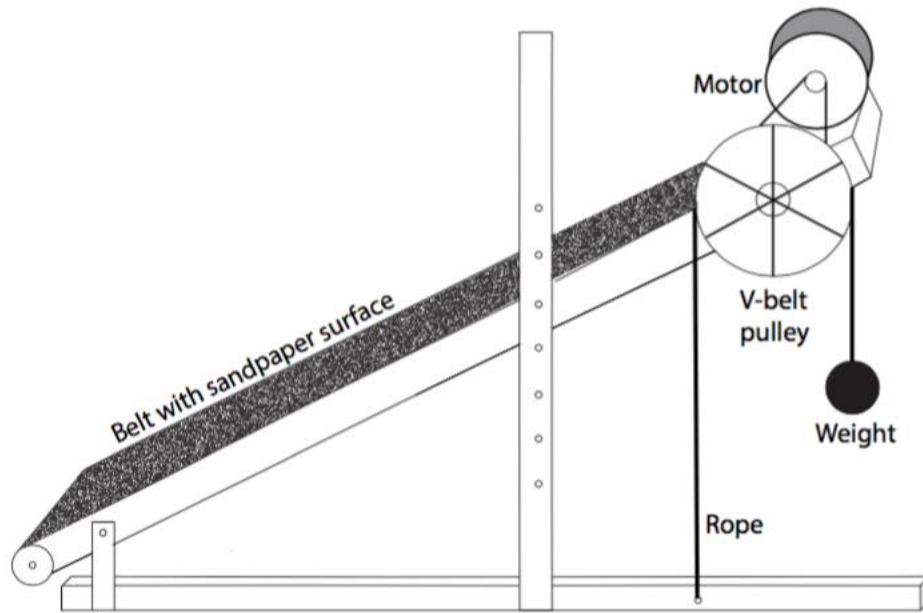


Figure 2. Customized treadmill mounted at 30°.

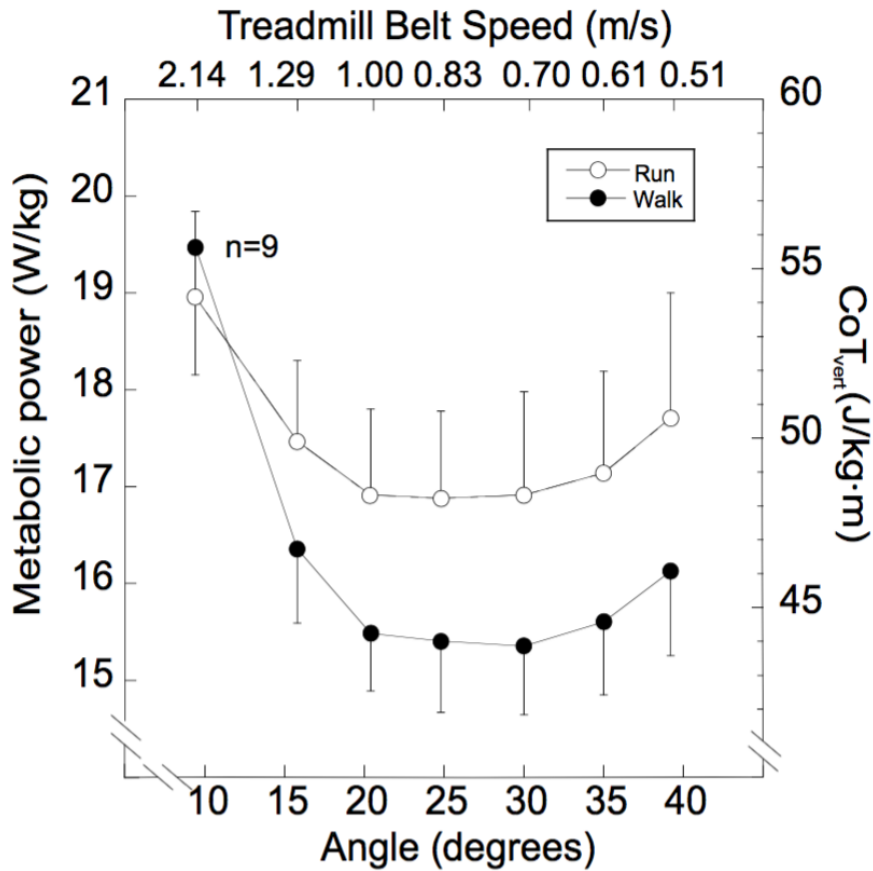
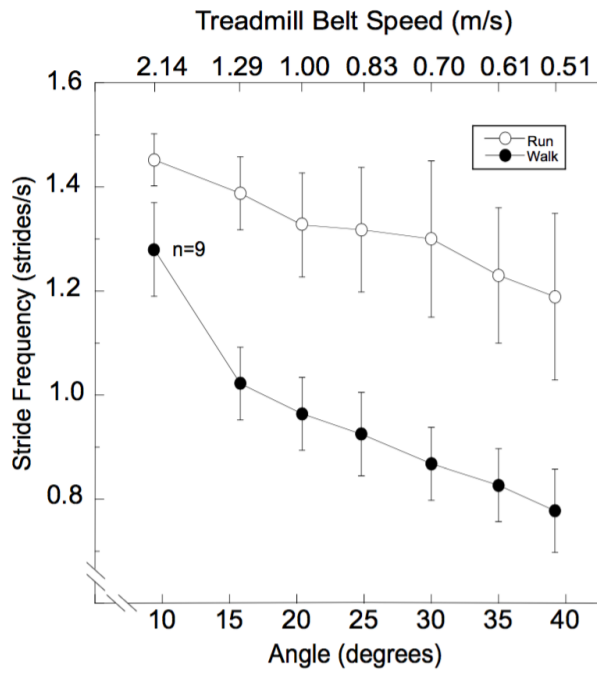


Figure 3. Metabolic power (W/kg) and vertical cost of transport (CoT_{vert} , J/kg·m) of walking (black circles) and running (white circles) plotted as a function of angle (degrees) and treadmill speed (m/s) for 15 subjects. At 9.4° only 9 subjects were able to walk at the required speed (2.14 m/s). Except for 9.4°, walking was less metabolically expensive than running. See text for more details.

4A



4B

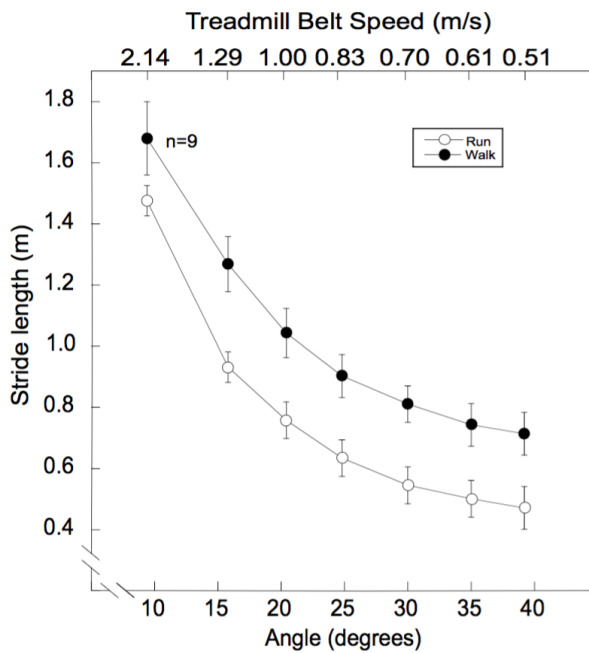


Figure 4. Stride frequency (strides/s, 4A) and stride length (m, 4B) for walking (black circles) and running (white circles) as a function of angle (degrees) and treadmill speed (m/s) for 15 subjects. At 9.4° only 9 subjects were able to walk at the required speed (2.14 m/s).

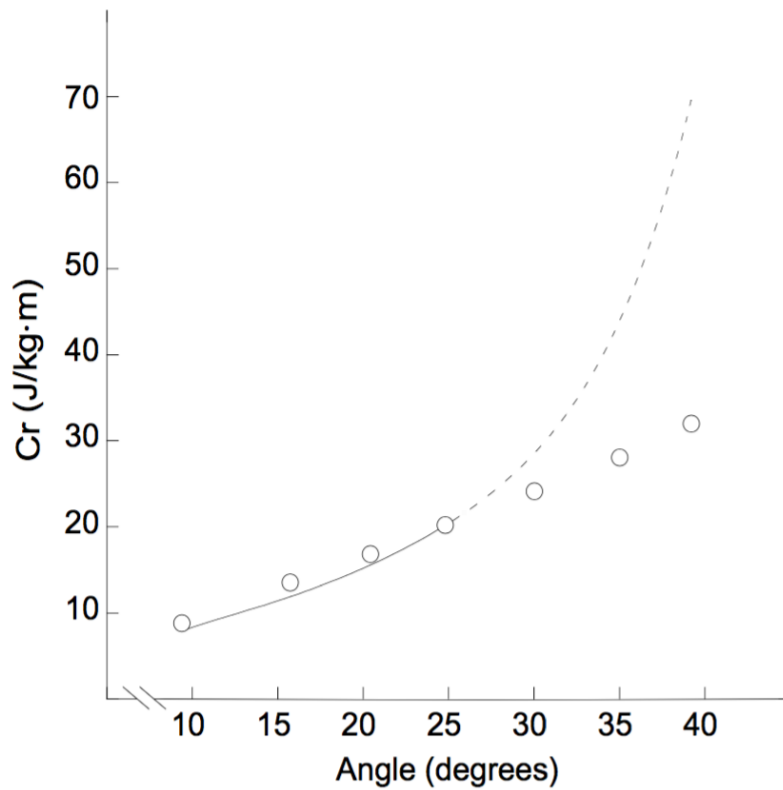


Figure 5. Mean cost of running (Cr, in J/kg·m) measured in the present study (white circles) and computed with the formula of Minetti et al. (21) (black line). The dashed line extrapolates to angles steeper than 24.2° (45%). The relationship between Cr and the slope for our data is described by the formula $Cr = 1.3614 + 0.7686 (\text{angle in degrees})$ ($R^2=0.97$).

Chapter III

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

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Keywords: uphill; cost of transport; energetics; economy

Abbreviations:

C_w Cost of Walking

C_r Cost of Running

RER Respiratory Exchange Ratio

VK Vertical Kilometer

ABSTRACT

Purpose: Vertical Kilometer (VK) races, in which runners gain 1000 m of elevation in < 5000 m of total distance, are becoming popular, yet there are few studies on steep uphill running.

Previously, we determined that $\sim 30^\circ$ is the optimal angle for uphill running, costing the least amount of energy for a given vertical velocity. In the present study, we quantified the metabolic cost of walking and running at various velocities at a 30° incline.

Method: At a 30° incline, eleven experienced runners (7M, 4F, 30.8 ± 7.9 years, 1.71 ± 0.08 m, 66.7 ± 9.4 kg) walked and ran for 5 minute trials with 5 minute rest between. Starting at 0.3 m/s, we increased treadmill velocity by 0.1 m/s for each successive trial until subjects were unable to maintain the set velocity. We measured oxygen uptake ($\text{mlO}_2/\text{kg}/\text{min}$) and metabolic rates (W/kg) and calculated the costs of walking (C_w) and running (C_r) ($\text{J}/\text{kg}/\text{m}$).

Result: Oxygen uptake and metabolic power increased linearly with velocity

($\text{W}/\text{kg walk} = 1.452 + 21.848v$, $\text{W}/\text{kg run} = 5.351 + 17.586v$). At the five slowest velocities (0.3, 0.4, 0.5, 0.6 and 0.7 m/s), C_w was less than C_r . However, at 0.8 m/s there was no difference between the two, and extrapolation suggests that at faster velocities, running likely costs less than walking.

Conclusion: Running quickly up steep inclines requires more energy than running slowly does.

Furthermore, at slower speeds, walking costs less than running. Thus, VK racers should pick a specific gait based on their racing speed.

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). 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 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° . (Note: Hoogkamer et al. (2014) found the relationship to be somewhat better fit at angles $< 9^\circ$ by adding an exponentially decaying term related to braking and propelling, but the relationship became more linear at steeper angles.) Thus, the overall relationship 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 and thus maximizes vertical velocity (Giovanelli et al., 2015). For both walking and running, angles ranging from 20.4° to 35.0° minimized metabolic cost for ascending at a vertical velocity of 0.35 m/sec. We reasoned that VK race courses with slopes in that range should yield the fastest times. Additionally, at 0.7 m/s on a 30° incline, walking required a 9.2% lower metabolic rate than running, suggesting that to minimize metabolic cost,

most competitors in a VK should walk rather than run. However, Giovanelli et al. did not determine how metabolic rate 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 running economy and maximal rate of oxygen consumption ($\dot{V}O_2$ max) (Joyner, 1991).

Our primary goal was to compare the rates of oxygen uptake and metabolic energy consumption for walking and running at one extreme uphill angle (30°) across a range of velocities. The men's VK world record of 29:42, set by Urban Zemmer, equates to an average running velocity of 1.08 m/s on a 31.4° incline, or an average vertical velocity of about 0.56 m/s. Thus, we chose to study the metabolic cost for walking and running at close to this VK pace and angle. From Giovanelli et al. (2015), we knew that at a 30° incline, walking is more economical than running at a treadmill belt velocity of 0.7 m/s. However, we sought to determine whether that is true at faster treadmill belt velocities that are more representative of competitive VK performances. We hypothesized that at 30° there is a particular velocity, above 0.7 m/s, at which running becomes more economical than walking.

Our second goal was to develop a standardized steep uphill treadmill protocol for testing mountain runners. For level running, there are a few such protocols commonly used by scientists to evaluate and compare level running economy. Typically, these protocols entail determining $\dot{V}O_2$ submax at between 4.5 and 3.8 m/sec (~6 to 7 minutes per mile pace or ~3:45 to 4:20 minutes per km) at a 0% or 1% incline (Jones et al., 2006; Farrell et al., 1979; Lucia et al., 2006; Weston et al., 2000; Morgan et al., 1995). Here, we propose an analogous running economy test specifically for mountain 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 ± 0.08 m, mass: 66.7 ± 9.6 kg, body mass index: 22.8 ± 2.4 kg/m²) volunteered and provided informed consent as per the University of Colorado Institutional Review Board. Subjects ranged from recreational runners to elite mountain runners.

Treadmill. As described by Giovanelli et al. (2015), we altered a custom treadmill, making it inclinable from 0 to 45°. In order to increase the treadmill belt's traction, we attached a wide swath of skateboard grip tape (Vicious Tape, Vancouver, BC Canada). In order to protect the treadmill motor, we attached three v-belt pulleys to the shaft of the drive roller and hung ropes with weights (about 8kg) 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-minute 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-minute trials. 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 m/s. Then, we incremented the treadmill velocity by 0.1 m/s each trial, continuing until subjects could no longer maintain a walk or run at

the given velocity. Subjects had 5 minutes of rest between trials. All 11 subjects were able to complete both the walking and running trials at treadmill velocities of 0.3 m/s, 0.4 m/s and 0.5 m/s. However, at 0.6 m/s only 10 subjects could complete both trials, at 0.7 m/s only 9 subjects could, at 0.8 m/s only 6 subjects could, and at 0.9 m/s only one subject was able to complete both walking and running trials while maintaining a respiratory exchange ratio (RER) <1.0.

Metabolic Measurements. To determine the metabolic rates 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 in order 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 minutes of each trial and calculated metabolic rate in W/kg using the Brockway equation (Brockway,1987). We calculated the cost of transport (J/kg/m) for walking (C_w) and running (C_r) by dividing metabolic rate by treadmill belt velocity. Because the treadmill was inclined to 30°, one can easily calculate the cost of transport per vertical meter by dividing by 2 because the sine of 30° is 0.5. Additionally, we only analyzed data recorded when a subject's RER was < 1.0.

Statistical analysis. Using R-Studio (www.rstudio.com), we performed paired t-tests to compare the rates of oxygen uptake, metabolic power and the cost of transport for walking versus running at each velocity. We used $p < 0.05$ as a criterion of significance.

RESULTS

Energetics of walking vs. running at 30°. As seen in Figures 1a and 1b, at 30°, oxygen uptake (ml/kg/min) and metabolic power (W/kg) increased linearly with velocity during both walking and running. At the five slowest velocities, the oxygen uptake rates, metabolic power requirements and costs of transport for walking were statistically less than that for running at

0.3m/s (n=11), 0.4 m/s (n=11), 0.5 m/s (n=11), 0.6m/s (n=10) and 0.7 m/s (n=9) (all $p < 0.004$). However, at 0.8 m/s there were no statistical differences between the two gaits (n=6; $p=0.13$, $p=0.18$, $p=0.18$ respectively). At 0.9 m/s, 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 Figure 2 the cost of transport (J/kg/m) for both walking and running, decreased at faster velocities, at least until 0.9 m/s. Counterintuitively, on a 30° incline for either walking or running it requires less energy per unit distance to go faster rather than slower.

Economy of uphill running in comparison to flat running. Running economy is defined as the oxygen uptake or metabolic rate for running at a standardized, submaximal velocity (Conley et al., 1980). To calculate the range of inter-individual economy values for steep uphill running, we used the $\dot{V}O_2$ values for subjects running at 0.8 m/s because of the tested velocities, it was the closest to an elite VK racing velocity. Percent range was calculated as $(\max \dot{V}O_2 - \min \dot{V}O_2 / \text{average } \dot{V}O_2) \times 100$. At 0.8 m/s, there was a 14% range in $\dot{V}O_2$ submax values (ml/kg/min) for the runners in this study. For slower velocities, the percent range in $\dot{V}O_2$ values were numerically slightly greater : 16% at 0.7 m/s, 18% at 0.6 m/s, 16% at 0.5 m/s, 19% at 0.4 m/s and 31% at 0.3 m/s.

DISCUSSION:

Our primary finding was that on a 30° incline, for both walking and running, metabolic rate increased linearly with velocity. Intuitively that makes sense; moving faster requires a faster energy supply. On inclines steeper than 9°, the primary determinant of metabolic energy consumption is the mechanical power required to lift the body against gravity (Minetti et al., 2002). When running up steep inclines, gross efficiency, the ratio of mechanical power to

metabolic power, is nearly constant. Therefore, metabolic rate increases directly with velocity on a given steep incline. The relationship between $\dot{V}O_2$ submax (ml/kg/min) at 30° and treadmill velocity, V in m/s, that we found for running is the following:

$$\dot{V}O_2 \text{ submax at } 30^\circ = 50.329V + 16.05 \quad r=0.956 \quad (\text{Equation 1})$$

Additionally, we found that on a 30° incline, for treadmill velocities between 0.3 and 0.7 m/s, the metabolic rate for walking was significantly less than for running. However, at 0.8 m/s the rates for walking and running converged and there was not a significant energetic difference between the two gaits. Only one of our subjects was able to complete the walking and running trials at 0.9 m/s aerobically, so although running was numerically less expensive than walking, we cannot accept our first hypothesis yet. Extrapolation of our data to velocities faster than we could test certainly suggest that running would become more economical, but confirmation awaits further testing on more elite athletes. Recall that the world record for the VK race is just under 30 minutes at a running velocity of 1.08 m/sec on a ~30° incline.

Our experimental design (30° at multiple velocities) revealed one counterintuitive finding. We found that at faster velocities, the cost of transport for both walking and running decreased, i.e. the metabolic cost per distance for walking or running up a hill is less at faster speeds. This suggests that during mountain running or hiking, a smaller amount of energy is required to ascend faster rather than slower. This finding may be applicable to ultramarathon runners who need to conserve energy in the beginning of a long race. For level running, plots of metabolic power vs. velocity plots have relatively small y-intercepts and as a result, the cost of transport for running is fairly constant across velocities. However, for steep uphill running, the y-

intercept is substantial. The high cost of transport at slow speeds 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 not apparent for either level or steep uphill running.

Of course, when racing, the goal is to minimize time, not energy expenditure per distance. In an endurance race of 30-40 minutes duration, the athlete must stay below $\dot{V}O_2$ max, even if it would hypothetically require less total energy to run faster. Daniels calculates that about 93% of $\dot{V}O_2$ max can be sustained for 30 minutes (Daniels et al., 1979). Therefore, an elite racer should determine a velocity that allows them to stay at about 93% of their $\dot{V}O_2$ max while also minimizing energy cost as much as possible. Athletes who cannot finish a VK in 30 minutes must run at a lower percent of their $\dot{V}O_2$ max. For example, a 45 minute VK runner can sustain about 90% of $\dot{V}O_2$ max. We have expanded on the competitive VK implications of our data in the Appendix.

Anecdotally, it seems that the fastest mountain runners are not the fastest track athletes and vice versa. Rather, athletes tend to specialize, perhaps allowing them to develop specialized biomechanical technique (skill), anatomy and/or physiology. Alternatively, elite mountain runners may be born, not made. Some have proposed that the degree of skill involved in a specific movement can be quantified by the inter-individual range of economy values for different people performing the same movement (Conley et al., 1980). For example, Daniels et al. (1984) found that among a group of runners there was a 13.1-18.2% range in economy for cycling, but only an 11% range for uphill walking. That finding implies that, because there was a larger range in economy for cycling than for grade walking, cycling requires more skill. That

idea is counterintuitive to us because it seems that there are many more biomechanical degrees of freedom during walking than cycling.

Daniels et al. (1984) found that a runner's economy for one mode of exercise was not related to their economy in other modes of exercise. One interpretation of that finding is that individuals do not have generalized intrinsic physiological factors (e.g. muscle mitochondrial functions) that allow them to be economical in all modes of exercise. Alternatively, it may be that extensive practice/training improves mode-specific economy. For example, a professional runner may be more economical at running than a professional cyclist, but when riding a bicycle, the opposite is likely true. In a retrospective analysis of seven studies, Morgan et al. 1995 found that within groups of similarly trained and accomplished athletes, running economy on a level treadmill ranged by $19\% \pm 2\%$ (Morgan et al., 1995). Previous studies report similar ranges (Conely and Krahenbuhl 1980; Williams and Cavanagh 1987).

Although the economy range for steep uphill running has not been extensively studied, Minetti et al. measured the economy of 10 runners on slopes up to 24.2° (Minetti et al., 2002). On level ground, at a velocity of 3.13 ± 0.22 m/s, their runners' oxygen uptakes averaged 35.5 ml/kg•min ± 2.7 SD. On the steepest measured slope, 24.23° , at a velocity of 0.89 ± 0.1 m/s, the average was 52.1 ml/kg•min ± 4.2 SD. Thus, the coefficient of variation (SD/mean) for level running was 7.7% while for steep running it was 8.1%. The similarity of those coefficient of variation values suggests that running uphill does not require more skill than running on level ground. On the other hand, Balducci et al. (2016), found that although the metabolic cost of running uphill increases with slope for all runners, the extent to which it increases varies by subject, suggesting that uphill running may be a skill that runners can develop by improving specific skills such as balance on uneven terrain.

Strictly using the inter-individual economy range metric, our data suggest that running uphill on a treadmill is not a learned skill. The percent range for $\dot{V}O_2$ values (ml/kg/min) was 14% for our runners up a 30° incline at a treadmill velocity of 0.8 m/s, which is close to a good runner's VK race pace. In comparison, in a previous study by Morgan et al. (1995), the percent range for $\dot{V}O_2$ values (ml/kg/km) for elite runners running on level surfaces was 18%. If running uphill is a learned skill, we would expect the percent range in $\dot{V}O_2$ values to be larger than that for runners on level ground. Note that the percent range from our study was smaller than that the Morgan et al. study on level ground, suggesting that uphill running is not be a learned skill. However, the percent range values that we compared are from different studies and the two samples were not very well matched (our subjects were 8 male and female runners of varying ability, while Morgan et al. used only elite male runners). In our study, the runners who were able to run at 0.8 m/s were all competitive mountain runners. Therefore, it is possible that there was not a large percent range in economy values in this group because they were all economical at running uphill. We cannot definitively explain the greater variability we found at at 0.3 m/s for which the percent range was much larger (31%). However, we think that this large range may be due to the fact that some subjects had trouble running rather than walking at such a slow speed. As a result, those subjects' $\dot{V}O_2$ values were high even though the speed was slow. On the other hand, some runners were able to run slowly without a problem. Therefore, the range in $\dot{V}O_2$ values was quite large, making the percent range large as well. Overall, we lack convincing evidence that uphill running is a special skill.

Limitations and future research. Our number of subjects (n=11), and number of elite runners (n=1) was limited. To ensure that results are applicable to specialized VK racers, future studies should expand the sample size using our protocol and include more elite mountain

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 rocky, rugged and uneven terrain which increases the energetic cost of running (Voloshina et al., 2015; Zamparo, 1992). Thus, our results probably underestimate the actual metabolic cost of 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 cost. 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 summary, we measured the metabolic costs of walking and running on a 30° incline across a range of velocities. We discovered that at a 30° incline, at faster velocities, metabolic rate increases linearly. In particular, the metabolic rate during walking is less than that for running at speeds between 0.3 and 0.7 m/s. However, trends indicate that at faster speeds, the opposite may be true. Additionally, we found that the metabolic costs of transport for both walking and running decrease at faster speeds, at least up to 0.9 m/s. Taken together, our data suggest that in order to maximize vertical ascent rate and minimize energy expenditure, recreational VK racers should choose to walk, but faster racers should run.

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Appendix:

In order to mathematically predict a runner's level VK time from their level 10km time, we started with the men's 10 km world record, 26:17, or 26.28 minutes. In order to run this time, a horizontal velocity of 6.34 m/s is required. We adapted the approach of Daniels and Gilbert (1979) to determine that the world record holder's $\dot{V}O_2$ submax when running at this velocity is 79.66 mlO₂/kg/min. Throughout the appendix, $\dot{V}O_2$ is in units of ml/kg/min, velocity (V) is in m/s, and time (t) is in minutes:

$$\dot{V}O_2 \text{ submax on level ground} = 0.37V^2 + 10.94V - 4.6 \quad (\text{Equation 2})$$

(Daniels and Gilbert 1979)

Next, we inserted the 10 km time in the following equation to calculate the percent of $\dot{V}O_2$ max that a runner could maintain when running for this amount of time. :

$$\text{Sustainable \% of } \dot{V}O_2 \text{ max} = 80 + 18.94393e^{(-0.013t)} + 29.9e^{(-0.19t)} \quad (\text{Equation 3})$$

(Daniels and Gilbert 1979)

For 26.28 minutes, that yielded 93.6%. Finally, using the $\dot{V}O_2$ submax of the runner (79.66 mlO₂/kg/min) and the percent of $\dot{V}O_2$ max that could be maintained for the runner's 10 km time (93.6%), we calculated that the $\dot{V}O_2$ max of the runner would be 85 mlO₂/kg/min. Assuming that performance in the VK is also dependent on $\dot{V}O_2$ max, using the same methods as above, but using Equation 1, our equation from this study, rather than equation 2, we found the $\dot{V}O_2$ submax required to run various VK times and then matched level 10 km times to VK times that required the same $\dot{V}O_2$ max. :

$$\dot{V}O_2 \text{ submax at } 30^\circ = 50.329V + 16.05 \quad (\text{Equation 1})$$

In order to match VK and level 10 km times, we also calculated the $\dot{V}O_2$ max for various VK times. We assumed that the VK race times would be slightly greater than their corresponding 10

km times. Therefore, we started with a 26.38 minute VK time because this is slightly slower than the world record 10km time which is 26.28 minutes. Running a 26.38 minute VK requires a velocity of 1.26 m/s. Using equation 1, we calculated that a runner's $\dot{V}O_2$ submax for that velocity would be 79.64 mlO₂/kg/min. Next, using equation 3, we determined that a runner can sustain 93.64% of $\dot{V}O_2$ max for 26.38 minutes. Finally, using the calculated $\dot{V}O_2$ submax and sustainable percent of $\dot{V}O_2$ max, we estimated that running a VK in 26.38 minutes would require a $\dot{V}O_2$ max of 85 mlO₂/kg/min, the same as the $\dot{V}O_2$ max required for the 10 km world record. In this case, the predicted VK time of the hypothetical runner was only 6 seconds slower than his level 10 km time (Table 2).

However, when we used the same method to equate other VK and level 10 km times, we found that this similarity was only coincidental for the world record time. For slower level 10 km times, the VK time slowed at a far greater rate (Fig 3). For example, for a 40 minute level 10 km runner, the calculated $\dot{V}O_2$ submax is 47.4 mlO₂/kg/min and the percent of $\dot{V}O_2$ max that can be sustained for 40 minutes is 91.27%. This means that the runner's predicted $\dot{V}O_2$ max is 51.93 mlO₂/kg/min. This $\dot{V}O_2$ max predicts a VK time of 55:24 which is over 15 minutes slower than their level 10 km time. To explain this difference in the relationship between level 10 km times and VK times, we explored the time ratio for all runners.

For all runners, the ratio between the two race distances: a level 10 km and a VK on a 30° course is 10 000m/2 000m or 5. However, the ratio of the race velocities is different for each person, depending on their aerobic capacity, $\dot{V}O_2$ max. Those who run a faster level 10 km have a smaller ratio of their 10 km velocity/VK velocity than slower runners do. By dividing the distance ratio by the velocity ratio we can calculate the time ratio between the two races. For a runner with a larger velocity ratio, the time ratio is closer to 1.0 than for slower runners. For

example, the men's 10 km world record holder runs a 26.28 minute 10 km, and his predicted VK time is 26.38 minutes. His distance ratio, as always, is 5. But, his velocity is 6.3 m/s for 10 km to 1.3 m/s for VK, which is a ratio of 4.8. This means that his time ratio (distance ratio/velocity ratio) is $5/4.8$ or nearly 1.0. Let us compare this to the time ratio of a 40 minute level 10 km runner whose predicted VK is 55 minutes. The ratio of the race distances is 5, but the ratio of the velocities is 4.2 m/s to 0.6 m/s which is a ratio of 7. This means that his time ratio is $5/7$ or 0.71 which is further from the almost 1.0 time ratio of the fastest runners.

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 Equation 1 for up 30° has a slope of 50.329 mlO₂/kg/min per m/sec. If we convert the units of Leger and Mercier (1984) for level running, the slope is 11.387 mlO₂/kg/min per m/sec. Thus, to run a little faster uphill costs far more energetically, than running a little faster on the level.

Tables and Figures:

Table 1 Metabolic power and cost of transport values for walking (C_w) and running (C_r)

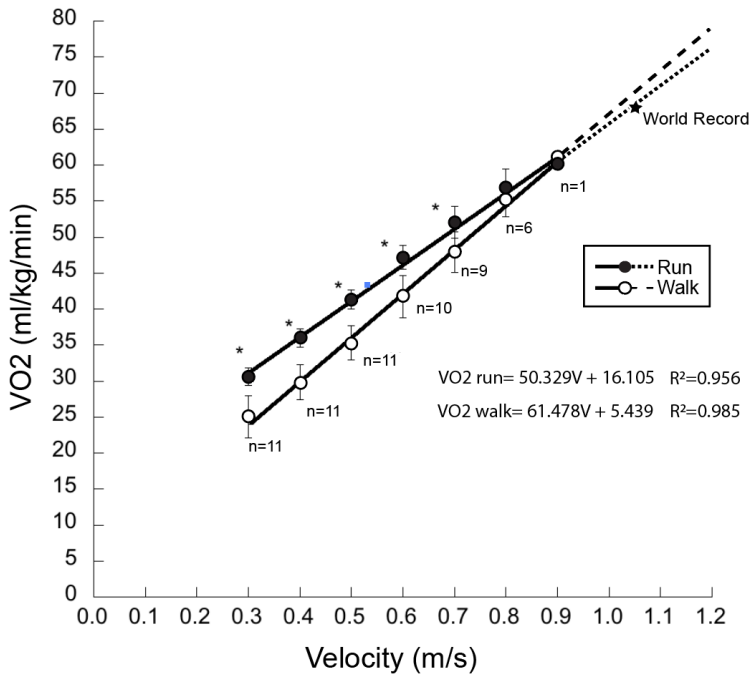
Velocity (m/s)	n	Walk Metabolic Power (W/kg)	C_w (J/ kg/m)	n	Run Metabolic Power (W/kg)	C_r (J/ kg/m)
0.30	11	8.60± 0.59	28.26± 1.37	11	10.30± 1.17	34.77± 3.42
0.40	11	10.29± 0.76	25.30± 1.06	11	12.07± 1.00	30.63± 2.02
0.50	11	12.21± 0.93	24.02± 0.84	11	13.92± 0.92	28.27± 1.64
0.60	10	14.51± 1.05	24.24± 1.08	10	16.02± 1.02	27.01± 1.77
0.70	9	16.50± 0.77	23.67± 1.08	9	17.87± 0.96	25.63± 1.41
0.80	6	19.16± 0.96	23.95± 1.20	8	19.72± 0.86	24.65± 1.08
0.90	1	21.34	23.71	1	20.59	22.88

*Metabolic power (W/kg) and cost of transport (J/kg/m) are reported as mean ± SD

Table 2 Level 10 km and equivalent VK running performance times

<u>10 km (min)</u>	<u>VK (min:sec)</u>
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 1
a



b

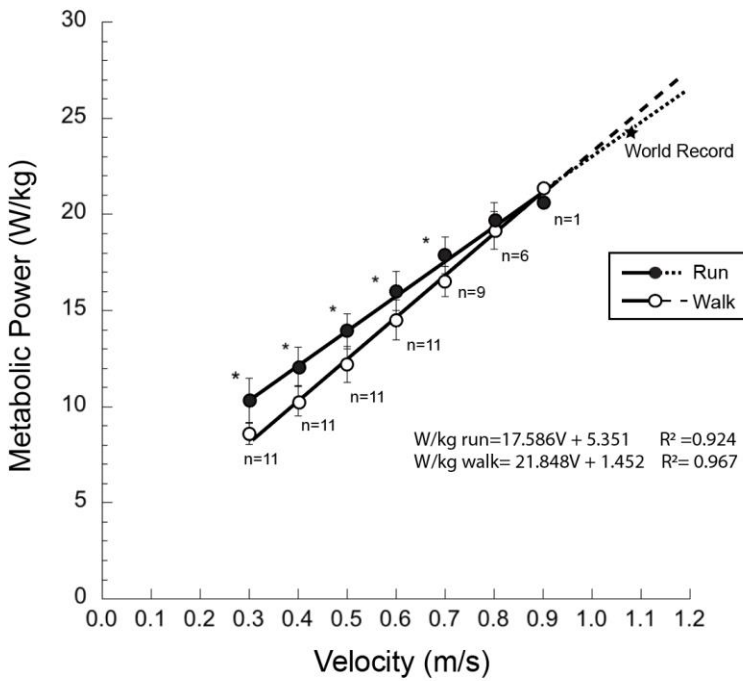


Fig 1 (1a) $\dot{V}O_2$ (ml/kg/min) and (1b) metabolic power (W/kg) as a function of treadmill velocity (m/s) at a 30° incline. Asterisks (*) indicate a statistically significant difference between walking and running at that velocity ($p < 0.05$). Error bars show SD

Fig 2

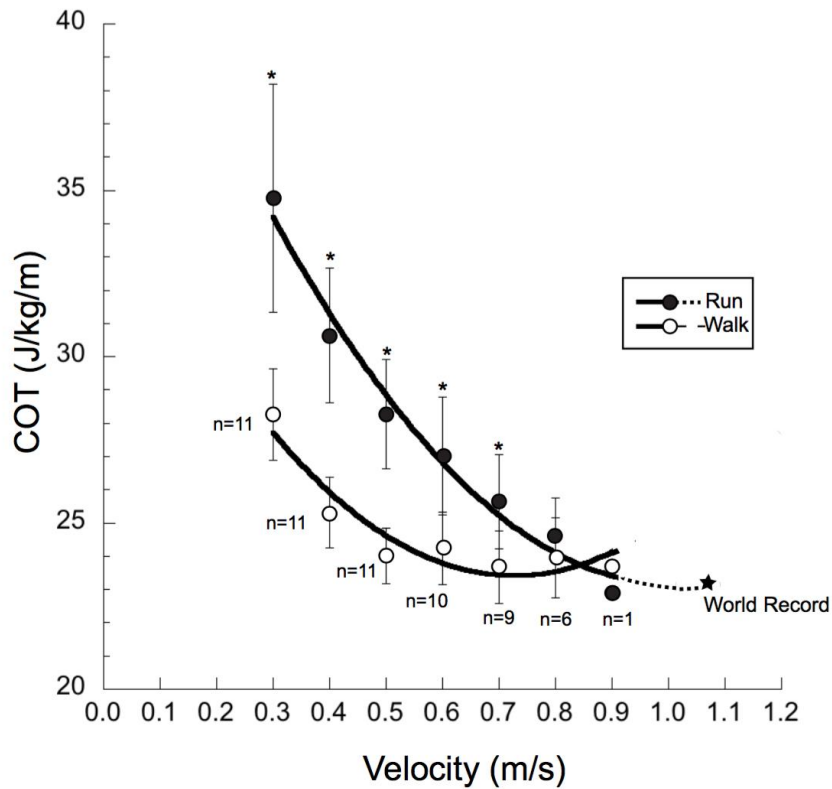


Fig 2 Cost of transport for walking and running at as a function of treadmill velocity (m/s) at 30° incline. Asterisks (*) indicate that there is a statistically significant difference between the cost of running and the cost of walking at that velocity ($p < 0.05$). Error bars show SD
 $COT_{run} (J/kg/m) = 22.02V^2 - 44.37V + 45.51$; $COT_{walk} (J/kg/m) = 23.60V^2 - 34.28V + 35.87$

Fig 3

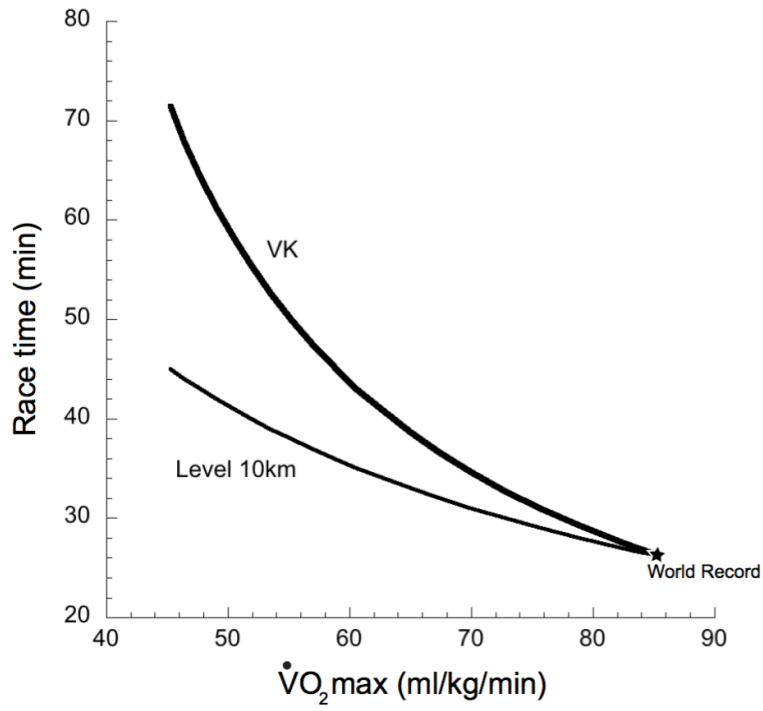


Fig 3 $\dot{V}O_2$ max (ml/kg/min) equivalent level 10 km and VK running performance times. See appendix for calculations