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ORIGINAL ARTICLE

Everesting: cycling the elevation of the tallest mountain on Earth

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Abstract

Purpose With few cycling races on the calendar in 2020 due to COVID-19, Everesting became a popular challenge: you select one hill and cycle up and down it until you reach the accumulated elevation of Mt. Everest (8,848 m or 29,029ft). With an almost infinite number of different hills across the world, the question arises what the optimal hill for Everesting would be. Here, we address the biomechanics and energetics of up- and downhill cycling to determine the characteristics of this optimal hill.

Methods During uphill cycling, the mechanical power output equals the power necessary to overcome air resistance, rolling resistance, and work against gravity, and for a fast Everesting time, one should maximize this latter term. To determine the optimal section length (i.e., number of repetitions), we applied the critical power concept and assumed that the U-turn associated with an additional repetition comes with a 6 s time penalty.

Results To use most mechanical power to overcoming gravity, slopes of at least 12% are most suitable, especially since gross efficiency seems only minimally diminished on steeper slopes. Next, we found 24 repetitions to be optimal, yet this number slightly depends on the assumptions made. Finally, we discuss other factors (fueling, altitude, fatigue) not incorporated in the model but also affecting Everesting performances.

Conclusion For a fast Everesting time, our model suggests to select a hill climb which preferably starts at (or close to) sea level, with a slope of 12–20% and length of 2–3 km.

Keywords Locomotion · Cycling efficiency · Uphill · Downhill

Abbreviations

CP	Critical power
GE	Gross efficiency
MAP	Maximal aerobic power
RPM	Revolutions per minute

Introduction

With cycling and running races canceled worldwide in the past years due to COVID-19, many cyclists looking for alternatives to test themselves took their fitness to Everesting: cycling up an elevation equivalent to Mount Everest (8,848 m or 29,029ft) as fast as possible (Jacobson 2020; Yeager 2020). The world records are well under 9 and 7 h for women and men, respectively, with average times recorded on Strava (an Internet service for tracking human exercise which incorporates social network features) around 17 h (Strava 2020). Since athletes can pick their course, gradient, and number of repeated ascents that gets them to the total of 8,848 climbed meters, Everesting presents an interesting scientific conundrum. Here, we explore this conundrum, aiming to determine the optimal slope and the optimal section length, and simultaneously putting our understanding of the energetics of cycling to the test in its ability to answer questions that athletes have.

Everesting has been around for at least 25 years, steadily growing in popularity over the past years. The first known Everesting ride was in 1994 by George Mallory, fittingly a grandson of mountaineer George Mallory who took part in the first three British expeditions to Mt. Everest in the 1920s. Mallory (the cyclist) needed 17 h to climb 8800 m; recently, the times for the full 8848 m climb have come

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down substantially. In May 2020, Katie Hall set a new record on the women's side, just missing the 10-h mark; since then, the record was broken three times, including Emma Pooley's 8:53:36 and with Illi Gardner as the current record holder with 8:32:38. On the men's side, the record has been broken six times, since Phil Gaimon took it under 8 h in May 2020, with Sean Gardner braking the 7-h mark in October 2020 and Ronan Mc Laughlin setting the current 6:40:54 record in March 2021.

With theoretically infinitely many options to pick a course, the question arises what would be the optimal course for Everesting. While the average grade does not differ much between the women's and men's records, the number of repetitions of each climb is highly variable. Current record holders Mc Laughlin and Gardner climbed their hill 76 and 71 times, respectively, but the women's previous record holder Pooley did her climb only ten times. Here, in the footsteps of Everest expedition physiologist Griffith Pugh (see Ward and Milledge 2002), we set out to find the factors that determine the optimal course for Everesting, based on state-of-the-art scientific insights. First, we address the biomechanics and energetics of up- and downhill cycling, and then, we discuss fueling strategy and the effects of altitude.

Optimal slope

Compared to running or walking, cycling is a highly efficient way of moving forward on smooth and level ground surface. During level ground cycling, a cyclist applies force on the pedals to overcome rolling and air resistance. The mechanical power produced by the cyclist and the sum of both counteracting forces will define the cycling speed (di Prampero et al. 1979). While rolling resistance is independent of speed, air resistance is proportional to the cyclist's (and wind) speed squared. To express both resistance forces as mechanical powers, we multiply them by the cycling speed

$$P_{\text{roll}} = C_r \times m \times g \times \cos\left[\tan^{-1}(\text{slope}/100)\right] \times v_c \quad (1)$$

$$P_{\text{air}} = 0.5 \times \rho_{\text{air}} \times C_d \times A \times {v_{c+w}}^2 \times v_c \quad (2)$$

where P_{roll} and P_{air} are the mechanical power outputs necessary to overcome the rolling resistance and air resistance, respectively. C_r is the coefficient of rolling resistance, m the mass of both cyclist and gear (bike, helmet, clothes, food, and drinks), g the gravitational acceleration, v_c the cycling speed, v_{c+w} the sum of the cycling and wind speed (note that a tailwind has to be subtracted from cycling speed), ρ_{air} the air density, A the cyclist's and bike's frontal area, C_d the coefficient of aerodynamic drag, and slope the incline of the hill expressed as a percentage (level ground cycling equals zero slope, and hence, the cosine term equals 1). Next to air resistance and rolling resistance, there are also drivetrain losses, usually estimated to account for a total loss of 2% (Martin et al. 1998). However, whether the measured mechanical power output already accounts for this loss depends on where it is measured. Pedal or crank-based power meters measure mechanical power output "upstream" of the drivetrain and therefore do not incorporate drivetrain losses (unless corrected for by the manufacturer's software), while power meters on the rear hub measure "downstream" of the drivetrain, and thus, the measured mechanical power is the power output with drivetrain losses already incorporated. Given these differences between power meters and the accuracy of those power meters (usually around 1–2%), we do not incorporate these drivetrain losses in our calculations.

Importantly, during uphill cycling, one additional factor comes into play compared to level ground cycling: the work against gravity

$$P_{\text{gravity}} = m \times g \times \sin\left[\tan^{-1}(\text{slope}/100)\right] \times v_c \quad (3)$$

Eventually, the sum of these three powers will be equal to the mechanical power output applied at the pedals and as such defines the cycling speed

$$P_{\text{mech}} = P_{\text{roll}} + P_{\text{air}} + P_{\text{gravity}} \quad (4)$$

To minimize the ascending time during an Everesting attempt, a cyclist wants to use most of their mechanical power output to overcome gravity (i.e., to gain elevation). Assuming a constant power output, a steeper slope will reduce the cycling speed and thus the related air resistance, resulting in a higher fraction of mechanical power being used to overcome gravity. This fraction of mechanical power that is used to overcome gravity at a specific slope depends on the combined mass of the cyclist and bike (and gear), and the total mechanical power output produced by the cyclist (Fig. 1a).

While mechanical power output is a valuable measure, ultimately, endurance cycling performance is determined by metabolic power (Horowitz et al. 1994; Passfield and Doust 2000). The ratio between metabolic power and mechanical power, i.e., gross efficiency (GE) is not constant as it depends (among other factors) on cadence. Interestingly, there is no clear consensus on the effect of slope on GE (Table 1). Arkesteijn et al. (2013) found that when cycling up an 8% slope, GE was 0.3 and 0.4% lower compared to cycling up a 4% slope or on level ground. Similarly, Nimmerichter et al. (2015) observed a 1.3% worse (lower) GE on a moderately steep 5.1% slope, as compared to a gentle uphill of 1.1%. In contrast, both Millet et al. (2002) and Arkesteijn et al. (2016) found on average slightly better GE on level compared to uphill, but these differences were not significant. Leirdal and Ettema (2011) compared level

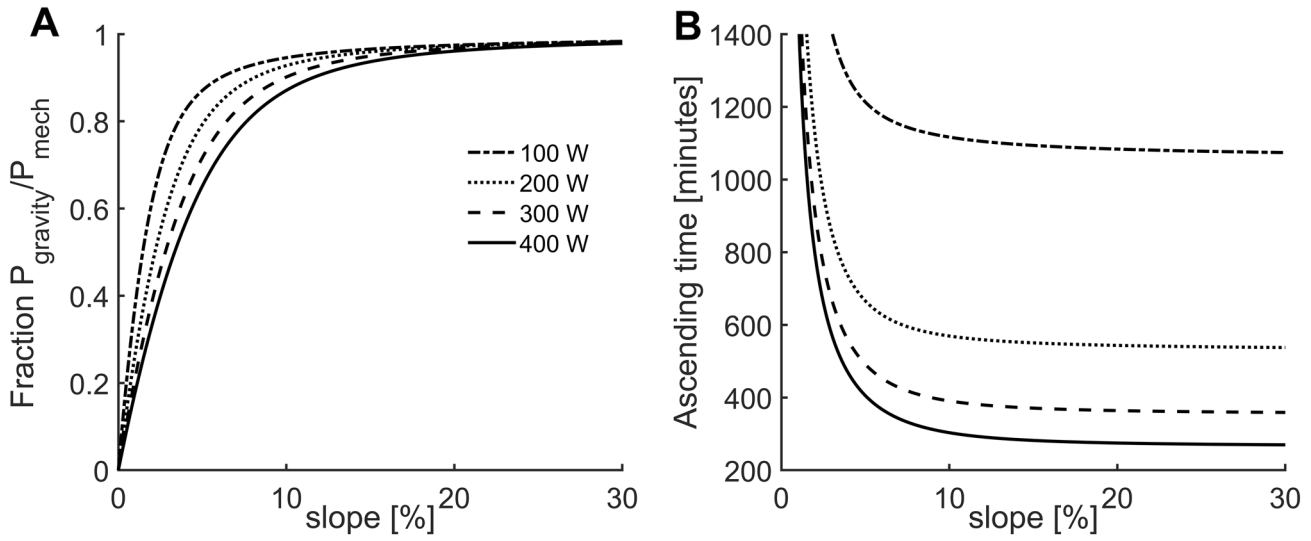

Fig. 1 **a** The relative amount of the mechanical power output produced by a cyclist to overcome gravity, when the absolute mechanical power output is 100 W (*dashed-dotted*), 200 W (*dotted*), 300 W (*dashed*), or 400 W (*solid*). A greater mechanical power output will result in a higher cycling speed, more air resistance, and therefore relatively less power available to overcome gravity. **b** The time to gain 8848 m of elevation as a function of the slope assuming a constant power output. Note that if slope equals zero ascending time will be infinite regardless of power output

Table 1 Overview of the studies comparing energy expenditure between uphill and level ground cycling or between different uphill grades

Study	*N*	Intensity (% maximal aerobic power)	Conditions	Equipment	GE
Millet et al. (2002)	8	75%	Level; 5.3%	Outdoor (velodrome/hill) crank power meter	No difference
Leirdal and Ettema (2011)	10	~57%	Level; 11%	Ergometer Velotron	No difference
Arkesteijn et al. (2013)	18	60–65%	Level; 4%; 8%	Treadmill rear hub power meter	$GE_{8\%} < GE_{flat}$ $GE_{8\%} < GE_{4\%}$ $GE_{4\%} \approx GE_{flat}$
Nimmerichter et al. (2015)	13	41%	1.1%; 5.1%	Outdoor crank power meter	$GE_{5.1\%} < GE_{1.1\%}$
Arkesteijn et al. (2016)	10	50%; 70%	4%; 8%	Treadmill rear hub power meter	No difference

ground cycling to a slope as steep as 11%, but did not find any difference in GE. While all these studies included trained cyclists, the cycling intensity varied substantially between studies, ranging from 41 to 75% of the maximal aerobic power (MAP, the highest average 1-min power performed during an incremental test on an ergometer), with the two studies that used the highest relative power output observing no difference in GE. Yet, the studies with the largest sample size did find a statistically significant lower GE while riding uphill, potentially indicating that other studies may have been underpowered. In addition, all but one study kept the cadence constant across slopes. In the study of Millet et al. (2002), cyclists adopted a much higher cadence during level ground cycling compared to uphill cycling (90 vs. 60 RPM) possibly explaining why no difference in GE was observed (see section on cadence below). In general, GE while riding uphill may be lower compared to level ground cycling, but the reduction seems to be rather small. Moreover, Wilkinson and Kram (2022) recently demonstrated that while riding up a 14.1% slope tilting the saddle nose down by 14.1% enhances cycling GE by 0.3% points (1.4%) compared to no saddle tilt (from 20.5 to 20.8%).

Figure 1b clearly shows that, to set a fast time, a hill with a slope exceeding 10% is most appropriate. Since the literature does not indicate a clear effect of slope on GE and since there are no data on steep slopes (≥ 12%), it is not possible to establish an optimal slope. Therefore, theoretically, a steeper slope will always result in a faster Everesting

time, unless GE starts to decrease substantially at steeper slopes. As an example: ascending the necessary 8848 m at an 8% slope in 6 h with a GE of 19.5% (Arkesteijn et al. 2013) will require 38,927 kilojoules.[1] At a steeper slope of 15%, this will require less metabolic energy, *unless* GE would decrease below 17.2%. It seems rather unlikely that GE would decrease by as much as 2.3% given the small—if any—differences reported for slopes up to 11%. Moreover, theoretically any reduction in GE when cycling uphill would have to be the result of slight changes in cycling position with incline. Hence, we reason that, by adapting the bicycle geometry [especially saddle tilt, as demonstrated by Wilkinson and Kram (2022), but potentially also saddle height, stem length, handlebar inclination, etc.], a cyclist should be able to obtain a similar GE at any slope. Nevertheless, a slope exceeding 20% will improve the uphill cycling time only by a limited extent (depending on the mechanical power output) and may impose other difficulties (i.e., gearing ratio, maintaining balance at low speeds or adapting cycling position, unsafe descents) making such steep hills possibly less suitable.

Cadence

While power output explains most of the variance in metabolic power during cycling (> 90%), cadence also affects metabolic power and thus GE (Ettema and Lorås 2009). Cyclists generally adopt a higher than optimal cadence, especially when riding on level surfaces (Lucía et al. 2001). There are several proposed mechanisms as to why cyclists do not optimize their cadence to obtain the highest cycling efficiency when riding on level ground surfaces (for a review, see Ettema and Lorås 2009). Yet, the effects of cadence on GE seem independent of slope (Leirdal and Ettema 2011; Arkesteijn et al. 2013; Nimmerichter et al. 2015) and reduce with increasing power output (Chavarren and Calbet 1999; Samozino et al. 2006). The cadence that a cyclist can adopt is determined by the cycling speed and gearing ratio of the bicycle (i.e., the ratio of the front sprocket to the rear sprocket). When riding up a steep hill the cycling speed is slow and the standard gearing ratio on a road bike imposes a low cadence. As an example, riding a road bike with standard climbing gearing of 36 × 30 at 10 km/h implies a cadence of 66 RPM. Moreover, the preferred cadence of high-performing cyclists is lower during uphill riding than during level ground cycling, even when the gearing ratio would allow for higher cadences (Lucía et al. 2001; Harnish et al. 2007). As such, the lower cadence during uphill cycling appears closer to the cadence associated with highest (best) GE.

Generally, the low cadence adopted when riding up a steep hill will not negatively affect GE when riding uphill. In addition, when Everesting on a steep, constant slope a cyclist will only need a few gearing ratios and selecting only these necessary gearing ratios [i.e., one for uphill, one for accelerating after a turn and one for downhill (if pedaling)] and removing all the other chain rings would reduce bicycle mass and which eventually could improve the climbing time. Interestingly, the current male Everesting record holder Mc Laughlin rode a "one by" setup (with only one single chain ring up front and no front derailleur) and stripped the cassette down to 7 sprockets (instead of the usual 11 sprockets) to save mass.

Standing vs. sitting

When switching from seated to standing cycling, joint angles drastically change, inducing changes in lower limb joint moments and powers (Caldwell et al. 1998, 1999; Tang et al. 2020; Wilkinson et al. 2020) and a slower preferred cadence (Harnish et al. 2007). During seated cycling, a part of the cyclist's body weight is passively supported by the saddle, whereas during standing, the body weight has to be actively supported by muscles but can also provide positive power during downstroke (Stone and Hull 1995), resulting in higher maximal power outputs reached during standing compared to sitting (Millet et al. 2002; Reiser et al. 2002). Furthermore, Hansen and Waldeland (2008) showed that the time to exhaustion during uphill cycling at high power outputs (> 94% MAP) is longer while standing compared to sitting.

Research on GE during seated and standing cycling has provided mixed results, possibly explained by differences in mechanical power outputs between studies (Table 2). At relatively low power outputs, seated cycling appears to be more efficient than standing (Ryschon and Stray-Gundersen 1991; Tanaka et al. 1996; Arkesteijn et al. 2016; Straw 2017). However, at higher power outputs, the difference in GE between seated and standing cycling diminishes (Tanaka et al. 1996; Arkesteijn et al. 2016) and some studies did not find any difference in energy consumption between both positions (Swain and Wilcox 1992; Tanaka et al. 1996; Millet et al. 2002; Harnish et al. 2007). While lower limb muscle activations are altered between seated and standing uphill cycling (Li and Caldwell 1998; Duc et al. 2008), the difference in GE between standing and seated cycling at relatively low intensity is most likely related to increased muscle activation of upper body muscles (activation to support body weight, stabilize pelvis/trunk, and provide lateral sway of the bike) (Millet et al. 2002; Duc et al. 2008). At higher intensities, however, forces applied to the handlebar increase in the

[1] Calculated using several assumptions: m = 73 kg (mass of cyclist, bike and all gear); C_r = 0.005 (Grappe et al. 1999); ρ_{air} = 1.22 kg/m^3; C_dA = 0.48 m^2 (García-López et al. 2008) and no wind.

Table 2 Overview of the studies comparing energy expenditure between seated and standing cycling

Study	*N*	Intensity (%maximal aerobic power)	Intensity (watts)	Conditions	Equipment	GE
Millet et al. (2002)	8	75%	~285 W	5.3%	Outdoor crank power meter	No difference
Ryschon and Stray-Gundersen (1991)	10	~55% VO_2max	NA	4%	Treadmill	$VO_{2,standing} < VO_{2,seated}$
Tanaka et al. (1996)	7	~60%; 84% VO_2max	NA	4%; 10%	Treadmill	$VO_{2,standing,4\%} < VO_{2,seated,4\%}$ $VO_{2,standing,10\%} \approx VO_{2,seated,10\%}$
Straw (2017)	12	NA	~213 W	7%	Treadmill crank power meter	$GE_{standing} < GE_{seated}$
Arkesteijn et al. (2016)	10	50%; 70%	~184 W; ~257 W	4%; 8%	Treadmill rear hub power meter	$GE_{standing} < GE_{seated}$
Swain and Wilcox (1992)	9	80% VO_2max	NA	variable	Treadmill	$VO_{2,standing} \approx VO_{2,seated}$
Harnish et al. (2007)	8	50%; 65%; 75%	~201 W; ~263 W; ~303 W	5%	Outdoor rear hub power meter	No difference

seated position as well, which may partly explain why the differences in GE at higher power outputs disappear (Millet et al. 2002; Duc et al. 2008).

The relative importance of the larger air resistance associated with standing (due to the larger frontal area compared to sitting) will reduce with lower cycling velocity (see Fig. 1a), making a steep hill (and thus low velocity) more suitable for standing cycling. Moreover, the increased upper body muscle activation while standing suggests a redistribution of the workload partly toward the upper limbs, possibly altering the mechanisms inducing fatigue during prolonged cycling. Hence, alternating between seated and standing climbing may delay and reduce fatigue during prolonged uphill cycling. Yet, it is recommended to then also train standing cycling given the different muscle coordination patterns between seated and standing climbing (Duc et al. 2008).

Optimal section length: critical power concepts

In contrast to what the name Everesting suggests, one is not supposed to really cycle to the summit of Mt. Everest. The goal is to overcome a positive elevation difference equal to the height of Mt. Everest by repeating one single section over and over again (note that one has to take the same way down as one rides up). One can choose the length of the section, and thus the number of repetitions, introducing the question what the most optimal number of repetitions would be. Previously, cyclists have chosen sections allowing just over 2 repetitions (cycling up volcano Mauna Kea in Hawaii) up to as many as 1001 repetitions. The optimal number of repetitions lies somewhere between both extremes, with the downhill sections allowing for some recovery between the uphill intervals, but time lost with every turn around when switching between uphill and downhill cycling. In 1969, Margaria and colleagues (Margaria et al. 1969) demonstrated that athletes can sustain supramaximal exercise intensities during repetitive short bouts of exercise (10 s) when enough rest was allowed (≥25 s) by relying on their aerobic and anaerobic alactic energy system. However, during Everesting, the duration of each uphill bout is unlikely to be this short (as it will result in many 180 degree turns; and the period of rest is presumably shorter than the duration of uphill cycling), making this approach not very applicable for Everesting. An alternative way to estimate the optimal number of repetitions is to apply the critical power concept for intermittent exercise to these uphill cycling intervals and downhill recovery bouts (Skiba et al. 2012; Jones and Vanhatalo 2017). This concept assumes that there is a power output, the critical power (*CP)*, which a cyclist can sustain "infinitely" long and a finite work capacity (W' in kilojoules) used when a cyclist exercises at an intensity above their *CP*. Once W' is depleted, exhaustion kicks in and the cyclist is forced to terminate exercise or at least "switch gears" and reduce power output below *CP*. When cycling above *CP*, W' is assumed to be depleted at a rate proportional to the difference between *CP* and actual power output (*P*)

$$W_{\text{int}} = (P - CP) \times t \tag{5}$$

with W_{int} the expended work capacity (W') during the interval and t the time since the start of the interval.

During recovery bouts between intervals, the depleted W' can be restored and, in contrast to the depletion of W', this restitution of W' is non-linear (Skiba et al. 2012)

$$W_{\text{rec}} = W_{\text{available}} + \left(W_0 - W_{\text{available}}\right) \times \left(1 - e^{-\frac{u}{\tau_w}}\right) \tag{6}$$

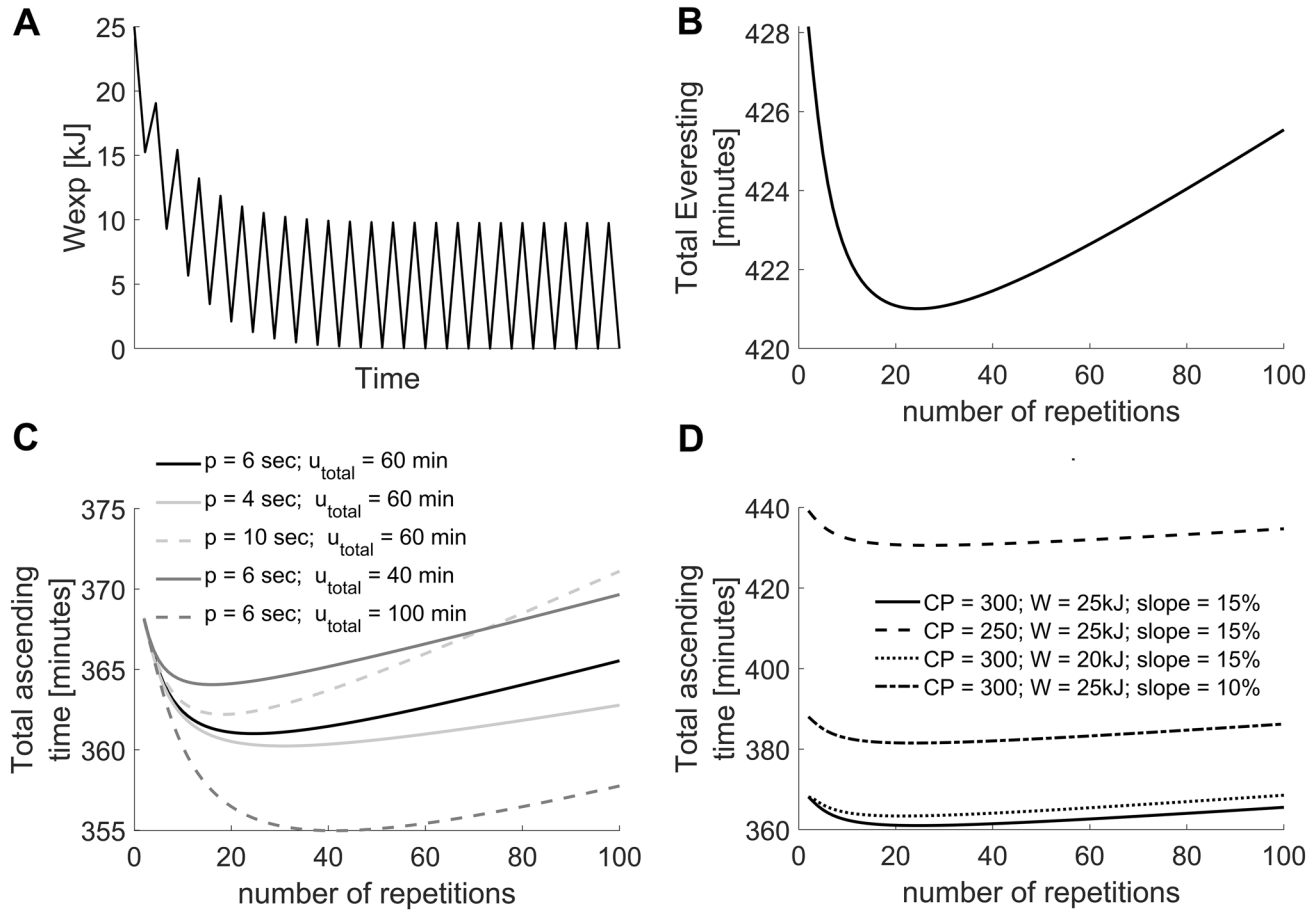

Fig. 2 Applying the critical power concept to determine the optimal number of sections. **a** Work capacity still available over time. **b** Total Everesting time as a function of the number of repetitions. **c** Sensitivity of total Everesting ascending time as a function of the number of repetitions with different assumptions for time penalty associated with additional repetitions and total downhill duration. **d** Total Everesting ascending time as a function of number of repetitions with different assumptions for a cyclist's physiology (*CP* and *W'*) and slopes

with W_{rec} the W' at the end of the recovery bout, $W_{available}$ the W' at the start of the recovery bout, W_0 the initial W' at the start of the ride when non-fatigued, u the time since the start of the recovery bout, and τ_w the time constant (in seconds) for restoring W'. Skiba et al. (2012) demonstrated that this time constant τ_w which determines the rate of recovery is negatively correlated with the difference in power output during recovery and CP (i.e., D_{cp}): the higher the difference (i.e., the lower the power output during recovery), the shorter the time constant, resulting in a faster recovery. Moreover, Skiba et al. (2012) provided an equation, specific for cycling, to calculate τ_W

$$\tau_W = 546 \times e^{-0.01 \times D_{cp}} + 316 \tag{7}$$

where D_{cp} is the difference between recovery power output and *CP*.

From these equations, we can now calculate how much of the rider's anaerobic work capacity W' is available throughout each uphill cycling interval

$$W_{available} = W_{rec} - (P - CP) \times t \tag{8}$$

with W_{rec} the W' at the start of a new interval, i.e., after recovery (note that for the first interval $W_{rec} = W_0$) (Fig. 2a).

These equations for linear depletion of W' during the uphill intervals and non-linear recovery of W' during downhill cycling indicate that theoretically infinitely short bouts of exercise are optimal. Yet, while Everesting, switching from an uphill to a downhill section (and vice versa) always comes with a U-turn. In addition, and especially while riding downhill, to enable a U-turn the speed has to be substantially reduced (i.e., through braking) wasting energy and time. Hence, a high number of repetitions (and thus short interval bouts) are less optimal than proposed by the model.

Therefore, we added a penalty for each repetition, assuming that two U-turns and the associated braking would add additional 6 s to the total Everesting time.

Applying the critical power concept

To allow us to implement the critical power concept to Everesting, we will have to make several assumptions for our rider (Skiba et al. 2012)

$$CP = 300W$$

$$W' = 25kJ$$

Furthermore, assuming that the rider only exploits gravity during the downhill sections and does not actively produce power ($D_{cp} = 300W$), allows us to calculate the time constant for restoring $W'(\tau_W)$

$$\tau_W = 546 \times e^{-0.01 \times D_{cp}} + 316 = 343.2s$$

Next, we also assume that the total descending time will be 1 h

$$u_{\text{total}} = 1\text{hour} = 3600s$$

The duration of one downhill section will depend on the number of repetitions (r) with

$$u = \frac{3600}{r-1}$$

Note that for the downhill recovery duration, we use $(r-1)$ as a successful Everesting attempt only requires the positive elevation of Mt. Everest to be completed, thus cycling down the last section is not incorporated in the total Everesting time. The fact that only positive elevation is relevant for Everesting may question the assumption of constant downhill cycling duration, especially with very long sections (and hence few repetitions).

From these equations, we simulated the power that a cyclist can sustain to overcome 8848 m of positive elevation on a 15% slope with a fixed total downhill duration of 1 h for a range of repetitions (2–100). Next, as we obtained the mechanical power output as a function of the number of repetitions, we determined the total Everesting time based on previous equations but added 6 s to the total time for every repetition. To calculate the power output sustained during uphill riding, an initial estimation was made for climbing time, re-adjusted after determination of the actual Everesting time, and sustained power and Everesting time were recalculated. This iterative process continued until the difference between the estimated and calculated ascending time was less than 1 s.

For our theoretical rider, the model predicts an optimal number of 24 repetitions (Fig. 2b). Of course, this optimal number of repetitions is sensitive to the assumptions made (Fig. 2c). Reducing the time penalty associated with turning increases the optimal number of repetitions (a penalty of 4 s corresponds with an optimal number of 31 repetitions) and also makes performing more repetitions than optimal less time costly. Reducing the total downhill cycling duration (i.e., recovery) reduces the optimal number of repetitions (16 for a total of 40 min downhill riding). Other assumptions associated with the rider's physiology (CP and W') have much larger effects on the total climbing time (Fig. 2d), but also some effect on the optimal number of repetitions. A CP of 250 W instead of 300 W increases the optimal number of repetitions to 27, while W' of 20 kJ instead of 25 kJ reduces the optimal number of repetitions to 21. Finally, the slope has a rather small effect (steeper would increase optimal number of sections slightly); however, note that usually the slope and total time of downhill cycling are somewhat correlated (steeper means faster downhills, assuming that there are no additional turns).

Other factors to consider

Other factors affecting the optimal section length—yet not incorporated in the model—are fatigue, turns, altitude, thermoregulation, and the possibility for resupply. In our simulations, we assumed a constant cycling GE. This GE value originates from studies in which trained cyclist performed constant power cycling for a relatively short period of time (ensuring steady-state metabolic rate but avoiding fatigue, i.e., less than 10 min). Yet, studies investigating the effect of prolonged cycling on GE have revealed a decrease in GE over time (Passfield and Doust 2000; Noordhof et al. 2015). Although the underlying mechanism of the decreased GE with prolonged cycling is unclear, during an Everesting attempt, GE will likely decrease over the time course of an Everesting attempt. This implies that, for the same metabolic power, less mechanical power is transferred onto the pedals, resulting in a reduced cycling speed and thus a longer Everesting time. Despite the reduction in GE, optimal section length is likely unaffected by fatigue. Furthermore, braking during the downhill when taking a sharp turn (i.e., hairpin turns) will slow the rider down, so a course with less turns will be faster. Next, the negative effect of reduced oxygen pressure at altitude on the performance ability, due to a reduction in VO_2max, is well recognized (Ferretti et al. 1997, 2011; Hahn and Gore 2001). Previously, di Prampero (di Prampero et al. 1979; di Prampero 2000) estimated the optimal altitude for a 1 h cycling record attempt accounting for the detrimental effect of altitude on VO_2max but also incorporating the reduced aerodynamic drag. While there is a benefit of reduced air density at altitude (lower aerodynamic drag), this benefit only outweighs the reduction in

VO_2max when cycling speed is high (e.g., the current world hour record for men (55.089 km; 15.3 m/s) is set at an elevation of 1800 m above sea level). Importantly, for Everesting, due to the low cycling speed when climbing, the reduction in VO_2max outweighs the benefits of reduced air density (for a slope of 15% at 300 W mechanical power, as little as 1.6% of metabolic power is used to overcome aerodynamic drag). Even at moderate altitude (i.e., 580 m), performance ability is decreased from reductions in VO_2max (Gore et al. 1997). Hence, an athlete should look for a hill climb which starts at an altitude close to sea level. Note that very long sections (allowing for very few repetitions) will inherently result in relatively high altitude at the end of the section. In our example, the model predicts an optimum of 24 repetitions, implying an increase in altitude of 369 m for every ascent. Given the detrimental effect of moderate altitude, it is possible that optimal number of repetitions in our model underestimates the actual optimal number of repetitions.

Also, thermoregulation is an important factor which needs to be considered in endurance performance, particularly in hot (and humid) environments. Evaporation and convection are the main contributors of heat dissipation during exercise, factors which are highly influenced by the relative air speed (Saunders et al. 2005). During uphill cycling, the cycling speed and thus relative air speed are low, and hence, overheating is a potential risk, impairing cycling performance (Gonzàlez-Alonso et al. 1999). In contrast, during downhill cycling, wind speed is high and heat can be more effectively dissipated. In general, to reduce the risk of overheating an Everesting attempt is better performed under rather mild or even cold conditions (Daanen et al. 2006; Hettinga et al. 2007). Due to the high absolute metabolic power and the related heat production sustained on the uphill sections, even in cold conditions, thermoregulation may remain an issue. Therefore, short uphill sections may further limit heat accumulation for each section and the subsequent downhill section may completely dissipate the excess of heat (Corbett et al. 2015).

As an Everesting attempt will last at least 6:40 h (i.e., current record) resupply is an important part of a successful attempt. While an optimal refueling plan is out of the scope of this paper, Everesting allows for easy refueling, and more importantly, shorter section length will allow for fewer additional food/fluids to carry on the bike (i.e., only food and fluids needed during one repetition). Note that one of the most important factors determining a fast Everesting attempt is mass (according to our model example 1 kg additional mass results in almost 5 min slower uphill time at 15% slope), and hence, additional mass from food and fluids (and the bike itself) should be minimized.

Conclusion and future work

In this paper, we set out to answer the question how the optimal hill for a fast Everesting attempt would look like. When aiming for a fast Everesting time, it is key to use most of one's mechanical power to gain elevation. The steeper the hill, the larger the fraction of mechanical power to gain elevation (Fig. 1a) making steep hills seemingly most appropriate (> 12%). However, at steep hills (> 20%), the fraction of mechanical power to gain elevation to the total mechanical power is close to one, making even steeper hills not much faster and, given the potential reduction in GE on steep slopes, we recommend a hill with a slope between 12 and 20%. In addition, tilting the nose of the saddle down seems to increase GE and as such reduce Everesting time (Wilkinson and Kram 2022). Next, by applying the critical power concept (Jones and Vanhatalo 2017), we determined the optimal number repetitions (i.e., section length). Our model predicts 24 repetitions to be optimal with the number slightly depending on the assumption made. Altogether, this leads us to a hill which preferably starts at (or close to) sea level, with a slope of 12–20%, 2–3 km-long sections and with no real turns. Other factors such as a good nutrition and hydration plan and selecting a day with mild temperatures and favorable wind will also help in setting your fastest Everesting time; these topics remain important factors for future research.

Other future work can further elaborate on this work, by, for example, incorporating altitude effects in the model or further optimizing the critical power concept and its related assumptions made in this manuscript (i.e., the time penalty for turning or the total downhill ride duration). Finally, while Everesting is a popular challenge in the cycling community, it is also gaining popularity in the running community. Future studies can use a similar approach to establish the optimal hill for a running Everesting attempt.

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Declarations

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

References

Arkesteijn M, Jobson SA, Hopker J, Passfield L (2013) Effect of gradient on cycling gross efficiency and technique. Med Sci Sports Exerc 45:920–926. https://doi.org/10.1249/MSS.0b013e31827d1bdb

Arkesteijn M, Jobson S, Hopker J, Passfield L (2016) The effect of cycling intensity on cycling economy during seated and standing cycling. Int J Sports Physiol Perform 11:907–912. https://doi.org/10.1123/ijspp.2015-0441

Caldwell GE, Li L, McCole SD, Hagberg JM (1998) Pedal and crank kinetics in uphill cycling. J Appl Biomech 14:245–259. https://doi.org/10.1123/jab.14.3.245

Caldwell GE, Hagberg JM, McCole SD, Li L (1999) Lower extremity joint moments during uphill cycling. J Appl Biomech 15:166–181. https://doi.org/10.1123/jab.15.2.166

Chavarren J, Calbet JAL (1999) Cycling efficiency and pedalling frequency in road cyclists. Eur J Appl Physiol Occup Physiol 80:555–563. https://doi.org/10.1007/s004210050634

Corbett J, Barwood MJ, Tipton MJ (2015) Physiological cost and thermal envelope: a novel approach to cycle garment evaluation during a representative protocol. Scand J Med Sci Sport 25:152–158. https://doi.org/10.1111/sms.12176

Daanen HA, Van Es EM, De Graaf JL (2006) Heat strain and gross efficiency during endurance exercise after lower, upper, or whole body precooling in the heat. Int J Sports Med 27:379–388. https://doi.org/10.1055/s-2005-865746

di Prampero PE (2000) Cycling on earth, in space, on the moon. Eur J Appl Physiol 82:345–360

di Prampero PE, Cortili G, Mognoni P, Saibene F (1979) Equation of motion of a cyclist. J Appl Physiol Respir Environ Exerc Physiol 47:201–206. https://doi.org/10.1152/jappl.1979.47.1.201

Duc S, Bertucci W, Pernin JN, Grappe F (2008) Muscular activity during uphill cycling: effect of slope, posture, hand grip position and constrained bicycle lateral sways. J Electromyogr Kinesiol 18:116–127. https://doi.org/10.1016/j.jelekin.2006.09.007

Ettema G, Lorås HW (2009) Efficiency in cycling: a review. Eur J Appl Physiol 106:1–14

Ferretti G, Moia C, Thomet JM, Kayser B (1997) The decrease of maximal oxygen consumption during hypoxia in man: a mirror image of the oxygen equilibrium curve. J Physiol 498:231–237. https://doi.org/10.1113/jphysiol.1997.sp021854

Ferretti G, Bringard A, Perini R (2011) An analysis of performance in human locomotion. Eur J Appl Physiol 111:391–401. https://doi.org/10.1007/s00421-010-1482-y

García-López J, Rodríguez-Marroyo JA, Juneau CE et al (2008) Reference values and improvement of aerodynamic drag in professional cyclists. J Sports Sci 26:277–286. https://doi.org/10.1080/02640410701501697

Gonzàlez-Alonso J, Teller C, Andersen SL et al (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032–1039. https://doi.org/10.1152/jappl.1999.86.3.1032

Gore CJ, Little SC, Hahn AG et al (1997) Reduced performance of male and female athletes at 580 m altitude. Eur J Appl Physiol Occup Physiol 75:136–143. https://doi.org/10.1007/s004210050138

Grappe F, Candau R, Barbier B et al (1999) Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance. Ergonomics 42:1361–1371. https://doi.org/10.1080/001401399185009

Hahn AG, Gore CJ (2001) The effect of altitude on cycling performance: a challenge to traditional concepts. Sport Med 31:533–557

Hansen E, Waldeland H (2008) Seated versus standing position for maximization of performance during intense uphill cycling. J Sports Sci 26:977–984. https://doi.org/10.1080/02640410801910277

Harnish C, King D, Swensen T (2007) Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs. Eur J Appl Physiol 99:387–391. https://doi.org/10.1007/s00421-006-0358-7

Hettinga FJ, De Koning JJ, de Vrijer A et al (2007) The effect of ambient temperature on gross-efficiency in cycling. Eur J Appl Physiol 101:465–471. https://doi.org/10.1007/s00421-007-0519-3

Horowitz JF, Sidossis LS, Coyle EF (1994) High efficiency of type I muscle fibers improves performance. Int J Sports Med 15:152–157. https://doi.org/10.1055/s-2007-1021038

Jacobson A (2020) How to cycle up 'mount everest. In: nytimes.com. https://www.nytimes.com/2020/08/13/sports/cycling/everesting-challenge-cycling-records.html. Accessed 1 Feb 2021

Jones AM, Vanhatalo A (2017) The 'critical power' concept: applications to sports performance with a focus on intermittent high-intensity exercise. Sport Med 47:65–78

Leirdal S, Ettema G (2011) The relationship between cadence, pedalling technique and gross efficiency in cycling. Eur J Appl Physiol 111:2885–2893. https://doi.org/10.1007/s00421-011-1914-3

Li L, Caldwell GE (1998) Muscle coordination in cycling: effect of surface incline and posture. J Appl Physiol 85:927–934. https://doi.org/10.1152/jappl.1998.85.3.927

Lucía A, Hoyos J, Chicharro JL (2001) Preferred pedalling cadence in professional cycling. Med Sci Sports Exerc 33:1361–1366. https://doi.org/10.1097/00005768-200108000-00018

Margaria R, Oliva RD, di Prampero PE, Cerretelli P (1969) Energy utilization in intermittent exercise of supramaximal intensity. J Appl Physiol 26:752–756. https://doi.org/10.1152/jappl.1969.26.6.752

Martin JC, Milliken DL, Cobb JE et al (1998) Validation of a mathematical model for road cycling power. J Appl Biomech 14:276–291. https://doi.org/10.1123/jab.14.3.276

Millet GP, Tronche C, Fuster N, Candau R (2002) Level ground and uphill cycling efficiency in seated and standing positions. Med Sci Sports Exerc 34:1645–1652. https://doi.org/10.1097/00005768-200210000-00017

Nimmerichter A, Prinz B, Haselsberger K et al (2015) Gross efficiency during flat and uphill cycling in field conditions. Int J Sports Physiol Perform 10:830–834. https://doi.org/10.1123/ijspp.2014-0373

Noordhof DA, Mulder RCM, Malterer KR et al (2015) The decline in gross efficiency in relation to cycling time-trial length. Int J Sports Physiol Perform 10:64–70. https://doi.org/10.1123/ijspp.2014-0034

Passfield L, Doust JH (2000) Changes in cycling efficiency and performance after endurance exercise. Med Sci Sports Exerc 32:1935–1941. https://doi.org/10.1097/00005768-200011000-00018

Reiser RF, Maines JM, Eisenmann JC, Wilkinson JG (2002) Standing and seated Wingate protocols in human cycling. A comparison of standard parameters. Eur J Appl Physiol 88:152–157. https://doi.org/10.1007/s00421-002-0694-1

Ryschon TW, Stray-Gundersen J (1991) The effect of body position on the energy cost of cycling. Med Sci Sports Exerc 23:949–953. https://doi.org/10.1249/00005768-199108000-00011

Samozino P, Horvais N, Hintzy F (2006) Interactions between cadence and power output effects on mechanical efficiency during sub maximal cycling exercises. Eur J Appl Physiol 97:133–139. https://doi.org/10.1007/s00421-006-0132-x

Saunders AG, Dugas JP, Tucker R et al (2005) The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. Acta Physiol Scand 183:241–255. https://doi.org/10.1111/j.1365-201X.2004.01400.x

Skiba PF, Chidnok W, Vanhatalo A, Jones AM (2012) Modeling the expenditure and reconstitution of work capacity above critical power. Med Sci Sports Exerc 44:1526–1532. https://doi.org/10.1249/MSS.0b013e3182517a80

Stone C, Hull ML (1995) The effect of rider weight on rider-induced loads during common cycling situations. J Biomech 28:365–375. https://doi.org/10.1016/0021-9290(94)00102-A

Strava (2020) The rise of everesting. In: strava.com. https://www.strava.com/clubs/231407/posts/13348654. Accessed 1 Feb 2021

Straw A (2017) The effect of suspension on the energetics and mechanics of riding bicycles on smooth uphill surfaces. University of Colorado Boulder

Swain DP, Wilcox JP (1992) Effect of cadence on the economy of uphill cycling. Med Sci Sports Exerc 24:1123–1127. https://doi.org/10.1249/00005768-199210000-00009

Tanaka H, Bassett DR, Best SK, Baker KR (1996) Seated versus standing cycling in competitive road cyclists: uphill climbing and maximal oxygen uptake. Can J Appl Physiol 21:149–154. https://doi.org/10.1139/h96-013

Tang Y, Wang D, Wang Y et al (2020) Do surface slope and posture influence lower extremity joint kinetics during cycling? Int J Environ Res Public Health. https://doi.org/10.3390/ijerph17082846

Ward MP, Milledge JS (2002) Griffith pugh, pioneer everest physiologist. High Alt Med Biol 3:77–87. https://doi.org/10.1089/152702902753639595

Wilkinson RD, Kram R (2022) Nose-down saddle tilt improves gross efficiency during seated-uphill cycling. Eur J Appl Physiol 122:409–414. https://doi.org/10.1007/s00421-021-04841-y

Wilkinson RD, Lichtwark GA, Cresswell AG (2020) The mechanics of seated and nonseated cycling at very-high-power output: a joint-level analysis. Med Sci Sports Exerc 52:1585–1594. https://doi.org/10.1249/MSS.0000000000002285

Yeager S (2020) Everesting is having a moment. In: bicycling.com. https://www.bicycling.com/training/a32587197/everesting-cycling-having-a-moment/. Accessed 1 Feb 2021