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The effects of course design (elevation undulations and curves) on marathon running performance: an *a priori* case study of the INEOS 1:59 Challenge in Vienna

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Contributions:

CT recorded the elevation change and GPS data, gathered information about the course, prepared Table 1 and Figure 1, wrote and edited sections of the manuscript.

WH verified and corrected errors in the elevation change and GPS data, helped to develop the overall strategy, prepared Table 1 and figures, wrote and edited sections of the manuscript.

KLS helped to develop the overall strategy, wrote and ran the simulation code, prepared figures, wrote and edited sections of the manuscript

PT measured the curve radii, prepared tables and figures, wrote and edited sections of the manuscript.

CJA helped to develop the overall strategy, prepared tables and figures, wrote and edited sections of the manuscript.

RK initiated the project, recruited the team, helped to develop the overall strategy, wrote the first draft of the manuscript and edited subsequent versions.

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KLS, WH and RK were paid for consulting service to the INEOS 1:59 Challenge. RK is a paid consultant to NIKE Inc.

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Abstract

Eliud Kipchoge is scheduled to attempt to run a marathon in 1:59:59 or faster on October 12, 2019. We used publicly available data to determine the undulations in elevation and the radii of the curves on the course. With previously developed equations for the effects of velocity, slope, and curvature on oxygen uptake, we performed simulations to quantify how much the elevation changes and curves of the Vienna course should affect oxygen uptake (at a fixed velocity) or velocity (at a fixed oxygen uptake). We estimate that, beyond a benefit from the downhill in the first 1 km of the course, oxygen uptake rates will fluctuate by no more than 2% of the oxygen uptake rates on a flat, straight course for km 1 to 42, leading to an overall increase in oxygen uptake of only 0.11%. Together, we estimate that the undulations and curves of the Vienna course incur a penalty of less than 5 s compared to a perfectly level and straight course. We do not have sufficient data to include aerodynamic drafting in our simulations but the course itself appears to be very well-chosen to minimize the negative effects of elevation changes and curves.

Introduction

Eliud Kipchoge, the current world record holder, will attempt to be the first person to run a marathon (42,195m) in less than 2 hours on October 12, 2019. This event will take place in Vienna (Austria) on a specially chosen course under the auspices of the INEOS 1:59 Challenge (www.ineos159challenge.com). The goal of this paper is to use publicly available information to evaluate the performance effects of the Vienna course, which comprises up and down undulations in elevation and curves.

At a specified velocity, running uphill requires a greater rate of metabolic energy supply (Margaria et al., 1963), primarily due to the mechanical work required to lift the center of mass (Hoogkamer et al., 2014). Thus, if a runner wishes to maintain a constant metabolic rate, they must run slower uphill. On the other hand, running downhill is metabolically cheaper because gravity provides some of the forward propulsion (Gottschall & Kram, 2005). However, for a specified slope angle, the increase in metabolic rate uphill is greater than the decrease in metabolic rate downhill (Margaria et al., 1963). This arises in part because performing negative work still has some metabolic cost, even though it is cheaper than positive work (Abbot et al., 1952). Marathon running records reflect those biomechanical and physiological facts.

A net downhill marathon course would provide substantial metabolic savings and thus faster performances, but the International Association of Athletics Federations (IAAF) regulations for record eligibility of a course limit the net elevation decrease to less than 0.1% of total race distance (i.e. 42m). The men's marathon record of 2:01:39 was set by Kipchoge in Berlin (Germany) on a course that has just one significant hill reaching an elevation ~20m higher than the start elevation, and no net elevation decrease from start to finish. In contrast, although many world-class trail runners have competed in the Pike's Peak marathon in Colorado (USA), the course record is much slower (3:16:39) due to the 2382m of elevation ascent and descent. Amusingly, the Pike's Peak half marathon ascent record is 2:01:06, almost exactly the same time as Kipchoge's full marathon record.

Choosing an ideal course was an important aspect of Breaking 2 (<https://en.wikipedia.org/wiki/Breaking2>), which was a previous attempt to run a marathon in under 2 hours. Breaking 2 took place in May 2017 on the Monza Italy auto racing track circuit. The Monza Breaking 2 course was a circuit of 2.424km in length with elevation fluctuations of about +/- 2.5m in elevation per lap. The course had long straight sections with turns ranging from 23m to 350m in radius. For reference, the inside lane of a standard outdoor 400m track has curve radius of 36.8m. Further, the Berlin marathon has ~43 turns some of which are 90-degree street corners. Taboga and Kram (2019) have recently modelled the energetic and associated time penalties incurred by running along a curved path. Curves require a runner to generate an additional centripetal force along the ground with their leg muscles. Thus, a runner effectively weighs slightly more when running along a curve and the greater effective weight increases the metabolic cost of running at a given velocity. Taboga and Kram estimated that the curves of the Monza racecourse imposed only a 1.5s penalty

compared to a perfectly straight course. With Kipchoge's remarkable physiology and determination, the relatively flat course, the mostly gentle turns, the steady pace car, and the phalanx of other runners that reduced aerodynamic drag all combined to produce at time of 2:00:25, the fastest marathon ever run. The elusive 25s is only 0.3% of the total time and thus small changes to the course or other factors may allow Kipchoge to finally break the 2-hour barrier.

From a purely energetics perspective, a perfectly level course should be superior to one with elevation undulations. Yet, some runners prefer mild undulations that slightly vary the demand on specific muscles. Likewise, the large radius turns of Monza were close to the theoretically optimal straight-line course. Yet, at the Monza Breaking 2 event, cheering fans were present only near the finish line of each lap and thus external motivation was likely sub-optimal. The record attempt in Vienna will mostly take place on a tree-lined ~9km out-and-back circuit (Hauptallee) (Figure 1) in a public park, repeated ~4 times which should maximize the positive effect of spectator cheering. The course features an initial 13m drop in elevation followed by an only slightly undulating elevation profile (+/- 3m per 9 km circuit). However, there are roundabouts (called: Praterstern and Lusthaus) at each end of the out-and-back straight circuit and their curvature radii range from 23 to 251m (Table 1).

Figure 1. Bird's eye view of the INEOS 1:59 Challenge course in Vienna, Austria.

Our analysis assumes that the supply of metabolic energy is the limiting factor in a marathon race (see Hoogkamer et al., 2017). For a basis of comparison, we use a hypothetical course that is perfectly flat and straight and a time of 1:59:59 (average velocity of 5.861 m/sec or 21.098 km/h). We use a previously published equation for the rate of oxygen uptake required for an individual runner to overcome air resistance and sustain an over-ground velocity of 5.861 m/sec (Kipp et al., 2019). We then estimate the metabolic energy and time benefits/penalties incurred by the elevation changes and curves of the Vienna course. Before proceeding, it is important to recognize that we lack publicly available information regarding the aerodynamic benefits afforded by the pacemaker runners and/or the lead automobile.

Table 1: Overview of the INEOS 1:59 Challenge course in Vienna, Austria, by segment.

Cummulative Distance (m)	Segment Distance (m)	start elevation (m)	Description	end elevation (m)	change (m)
0	1064	174	Reichsbruecke bridge & Lassalleestrasse (straight)	161	-13
1064	375	161	Praterstern after start (curve radii = 50-251 m)	161	0
1439	4250	161	Hauptallee South East (straight)	158	-3
5689	210	158	Lusthaus (curve radii = 23-135 m)	158	0
5899	4250	158	Hauptallee North West (straight)	161	3
10149	870	161	Praterstern (curve radii = 50-251 m)	161	0
11019	4295	161	Hauptallee South East (straight)	158	-3
15314	210	158	Lusthaus (curve radii = 23-135 m)	158	0
15524	4250	158	Hauptallee North West (straight)	161	3
19774	870	161	Praterstern (curve radii = 50-251 m)	161	0
20644	4295	161	Hauptallee South East (straight)	158	-3
24939	210	158	Lusthaus (curve radii = 23-135 m)	158	0
25149	4250	158	Hauptallee North West (straight)	161	3
29399	870	161	Praterstern (curve radii = 50-251 m)	161	0
30269	4295	161	Hauptallee South East (straight)	158	-3
34564	210	158	Lusthaus (curve radii = 23-135 m)	158	0
34774	4250	158	Hauptallee North West (straight)	161	3
39024	870	161	Praterstern (curve radii = 50-251 m)	161	0
39894	2301	161	Hauptallee South East to finish (straight)	160	-1
42195					

Methods

Course Quantification

Starting with an overview of the Vienna course (www.ineos159challenge.com) an investigator in an automobile and on a bicycle followed the green line on the pavement marking the route approximately 10 days prior to the race (Figure 1). The investigator recorded elevation with a resolution of 0.2m with a barometric pressure-based altimeter

(Edge 520, Garmin International Inc., Olathe, Kansas, USA) and simultaneously recorded GPS coordinates so that the location of the elevation data points could be sampled at 1-s intervals. The investigator traversed the course several times to obtain representative data. The data were then interpolated and smoothed to eliminate obvious errors and compiled into a data file specifying the cumulative race distance and elevation change for each 1m of the 42,195m total course length (Figure 2 and Appendix 1).

Knowing the course route, an investigator measured the radius of curvature using Google Earth. Each turn and roundabout were broken into distinct segments. The curvature measurements are depicted in Figure 2 and are also included in the data file in Appendix 1.

Figure 2. Elevation profile (A) and curvature (radius) of the Praterstern (B) and Lusthaus roundabouts (C) of the INEOS 1:59 Challenge course in Vienna, Austria.

Computational Methods

We used two distinct methods to calculate the differences between a flat, straight course and the Vienna course. The first method fixed the velocity at the 5.8612 m/s necessary to run a 1:59:59 marathon and tracked how elevation changes and curvature consequently changed the estimated oxygen uptake rate using equations from

Hoogkamer et al., (2014), Kipp et al., (2019) and Taboga and Kram, (2019), see below. Since limited data are available on the oxygen uptake rates for downhill running, we used data from Snyder and Farley (2011) to estimate the linear decrease in oxygen uptake as the downhill slope increases from 0 to 3 degrees. This required interpolation, because the maximum downhill slope on the Vienna course is 2.4 degrees. The second method fixed the estimated oxygen uptake at the value predicted by Kipp et al. for a straight, level course and then adjusted the velocity during uphill and downhill sections and in the curves to keep oxygen uptake constant throughout the race.

To estimate oxygen uptake rate ($\dot{V}O_2$) at a specific level running velocity, we used the equation from Kipp et al. (2019) (Eq. [1]). To estimate equivalent level velocities for running up a given slope (θ), we used the equation for cost of transport (CoT) by Hoogkamer et al. (2014) (Eq. [2]). To estimate the rate of oxygen uptake for running on a curve ($\dot{V}O_{2_curve}$) in terms of the radius of curvature (r) at a given velocity (v) with a given oxygen uptake rate, we used the equation by Taboga and Kram (2019).

$$\dot{V}O_2 = 0.02724v^3 + 1.7321v^2 - 0.4538v + 18.911 \quad [1]$$

$$CoT = 2.74 + 0.67e^{-18.24 \sin \theta} + \frac{g}{0.24} \sin \theta \quad [2]$$

$$\dot{V}O_{2_curve} = \left(0.6234 \sqrt{\frac{1+v^4}{gr^2}} + 0.3766 \right) \dot{V}O_2 \quad [3]$$

We also simulated a Vienna course with no turns to isolate the effect of just elevation changes on finishing time. Conversely, we simulated a Vienna course with no elevation changes to isolate the effect of turns on finishing time.

Results

Our simulations suggest that the Vienna course is only ~4.5s slower than a perfectly level and perfectly straight 42,195m course. If running velocity is fixed at 1:59:59 pace, the mean oxygen uptake rate will need to be 0.11% greater. We estimate that the initial downhill segment on the Reichsbrücke bridge will provide a ~6.0s (or 0.099%) benefit. On a hypothetical straight course with the elevation profile of the Vienna course, the elevation undulations on the Hauptallee would negate the 6s gain, resulting in an overall 4.1s loss due solely to elevation changes (or 0.095% oxygen uptake).

The curves by themselves only impose a small penalty of 0.49 seconds (or 0.011% oxygen uptake). Figure 3A shows changes in running velocity due to both slope and curvature, when rate of oxygen uptake is fixed. Other than the 6.6161 m/s peak velocity during the initial segment running down the bridge, the velocity fluctuations are small (range = 5.7985-5.8825 m/s). Logistically, fixing the running velocity via a pace vehicle is much simpler than adjusting velocity to maintain a constant oxygen uptake rate. On the Vienna course, except for a brief decrease in oxygen uptake rate (to 81.55% of the average rate of oxygen uptake) during the first 500 meters down the bridge, a constant

velocity requires only small variations in oxygen uptake rate (range=99.4-101.8% of the average; Figure 3B).

Figure 3: A) Pace (minutes per kilometer) for a flat straight course (blue) and for the Vienna course (red) with fluctuations due to undulation and curvature B) Percentage of oxygen uptake rate for a flat straight course (blue) and for the Vienna course (red); 100% equals rate for level, straight running.

Discussion

Our simulation results indicate that the Vienna course was well-chosen for optimizing performance. The penalty in time due to elevation changes and curvature of the Vienna course is quite small, only 4.5s or 0.06% of the total time. Further, the vast majority of this difference (4.1s) is due to elevation changes, with curvature only incurring just under half a second. The largest time benefit comes from the bridge downhill in the first 580m. Beyond the first 1km, the penalty due to the uphill outweighs the time gained on the downhills, leading to a net penalty. Compare this to the maximum possible net downhill elevation change (42 m), which would lead to a 19.26 s benefit on a straight course (which would be in violation of IAAF rules) or 18.76s, if the course were to follow the same curves but feature a consistent drop in elevation.

Though time may be a more intuitive measure, we believe it makes much more sense logistically to fix the velocity than it does to try to minutely adjust the pace to minimize changes in Kipchoge's oxygen uptake rate. If a fixed velocity strategy were used, beyond the large metabolic 18% benefit in the first 580 meters, there would be less than 2% change in overall oxygen uptake throughout the rest of the course. A 42m downhill course would lead to an 0.4372% reduction in oxygen uptake.

There are some limitations to our model. Notably, our assumption of a linear decrease in oxygen uptake rate on downhill slopes. Additionally, the equation from Hoogkamer et

al. (2014) assumes a linear equation for the cost of transport with velocity, whereas the Kipp et al. (2019) equation utilizes a curvilinear relationship. Further, Kipp et al.'s equation was determined from velocities ranging from 2.22 to 5.0m/s for sub-elite runners who likely have higher rates of oxygen than elite runners. Therefore, it is possible that the increase in oxygen uptake at 1:59:59 pace (5.8612m/s) is somewhat smaller than predicted by the Kipp et al. equation. The data and equations were determined for non-elite runners. Kipchoge is considered by many to be the greatest marathon runner in history with unique or at least extreme physiology, the coveted $n=1$.

There are other notable factors (e.g. aerodynamics, footwear) that we did not have sufficient data to model. Compared to the elevation changes and curves on the Vienna course, headwinds, tailwinds, pacesetter group configuration and footwear could have a much greater effect on oxygen uptake rates. Based on the work by Pugh (1971), we calculated earlier that tailwind or running behind a team of other runners can save an elite runner 2-3 minutes or more (Hoogkamer et al., 2017; Hoogkamer et al., 2018B). While Pugh (1971) found that there was a 6.5% reduction in oxygen uptake due to drafting behind a single pacemaker, his data were collected on a single subject running immediately behind another runner. Other pacing formations may lead to still greater metabolic benefit. Further, the change in oxygen uptake rate in response to small backwards pulling forces applied during treadmill running varies widely between subjects (Hoogkamer et al., 2019). The drafting strategy used in Vienna and Kipchoge's individual metabolic response to small drag forces will likely affect his chances of running <1:59:59 far more than the small oscillations in elevation or the curves on the course. Finally, running footwear has substantially improved over the past years, with observed metabolic energy savings of 4% between established marathon racing shoes (Hoogkamer et al., 2018A). Again, the individual response of Eliud Kipchoge in those shoes or updated prototype shoes is not known.

In conclusion, we found that the course is well-chosen to give Eliud Kipchoge his best chance of running 1:59:59. Beyond the beneficial downhill on the first 1K of the course, at a constant velocity, the estimated oxygen uptake will not fluctuate more than 2% above or below average, and the overall penalty is a mere 0.106%. While there are other factors that could affect his chances, such as the drafting strategy, the course will have a minimal effect. We the authors look forward to the Vienna event and wish Mr. Kipchoge the best of luck at making sporting history.

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