Speed and incline during thoroughbred horse racing: racehorse speed supports a metabolic power constraint to incline running but not to decline running.

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Racehorse speed with incline and decline

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Abstract
We used a radio tracking system to examine the speed of 373 racehorses on different gradients, on an undulating racecourse, during 33 races, each lasting a few minutes. Horses show a speed detriment on inclines (0.68 ms⁻¹/1% gradient, \( r^2 = 0.97 \)), the magnitude of which corresponds to trading off the metabolic cost (power) of height gain with the metabolic cost (power) of horizontal galloping. A similar relationship can be derived from published data for human runners. The horses, however, were also slower on the decline (-0.45 ms⁻¹/1% gradient, \( r^2=0.92 \)). Human athletes run faster on a decline, which can be explained by the energy gained by the COM from height loss. This study has shown that horses go slower, which may be attributable to the anatomical simplicity of their front legs limiting weight support and stability when going downhill. These findings provide insight into limits to athletic performance in racehorses which may be used to inform training regimes, as well as advancing knowledge from both veterinary and basic science perspectives.

Key words:
Biomechanics; horse; athletic performance.

Introduction
Maximal running performance with a duration of several minutes is taken to be limited by energy supply to muscles, which is derived from aerobic and anaerobic metabolism. In competitive events, such as middle and long distance running in horses, humans and sled dogs, it is usually accepted that best performance results from an even paced effort (25) or, more recently, with the advent of heart rate monitoring, a constant metabolic load (1). With shorter events, the mean speed is higher and the metabolic power greater, since the maximum rate of energy supply achieved through aerobic and anaerobic pathways drops with duration. When athletes run up hill they need to perform work to raise the centre of mass (COM) against gravity (mgh), which can be given as a power mg\( v_v \) (where \( v_v \) is vertical velocity). The relationship between vertical velocity and horizontal velocity (orthogonal to gravitational acceleration) is given by the gradient (s), so vertical velocity is \( v_v = v_h \cdot s \) and vertical power is \( v_h \cdot s \cdot mg \). This potential energy power is in addition to the metabolic work of horizontal running and has some role in the observation that athletes run slower up hill. Human and equine athletes undertake interval training up hills (horses almost exclusively so) to maximise...
metabolic load and training effect, whilst reducing the injury risk of higher speed running. Humans sometimes train downhill to increase running speed (17) but horses do not.

When an athlete runs downhill, they lose potential energy (PE) which is absorbed into the musculoskeletal system. If they were a wheel or ball, on a gradual slope, the accelerative component of the force due to gravity would equal frictional or aerodynamic drag forces, and speed and kinetic energy would remain constant. On a steeper slope, the ball would accelerate, gaining speed and hence kinetic energy. In downhill running, the potential energy input to the athlete compensates for some of the energy losses in the locomotor cycle. On moderate slopes VO₂ is lower, whilst on a steeper slope VO₂ will rise again (16). The rise on steep declines is likely due to muscles having to absorb potential energy, which has a metabolic cost and possibly results in a less economical running gait.

In human athletes, a relationship has been derived for the positive and negative benefits of incline and decline sections whereby the speed detriment of moving up an incline is approximately double the benefit of moving down an equivalent decline (2). A similar relationship has been derived for the disadvantage of a headwind vs the benefit of a tailwind, and for the reduced drag of running at altitude (2, 22). In competitions where races have a net downhill gradient, running speeds are consistently high, for examples see 5th Avenue Mile and Boston Marathon. In 1983 a 3:28 mile time, 19 seconds faster than the mile world record (at that time), was recorded on a downhill road course in New Zealand (10). Times achieved in the Boston Marathon are considered invalid for international records as the finish is substantially lower in elevation (drop of 3.2m for every km), and is too far from the start (91% separation and therefore possibility of constant tailwind). These studies and data show that there is a metabolic component to constraining gradient running performance which will result in slower top speeds at increased incline and faster top speeds on a decline, when compared to level running.

Incline locomotion represents a well defined additional power requirement due to potential energy gain. In horses, the work is achieved through increasing the frequency of cyclic contractions and the work per cycle (18). This increase in power requirement is reflected in an increase in metabolic cost (4, 33) with a 250% increase on a 10% incline compared to level trotting at the same speed (33). Conversely, oxygen consumption has been shown to
decrease on a decline in trotting horses and the speed at which minimum cost of transport (COT) occurs is faster than on the level (9).

Here we investigate metabolic power as a potential limit to maximum running speed by measuring speed during racing on an undulating racecourse. When a horse runs an uphill section of a constant effort race, it must perform potential energy work, additional to the metabolic work of forward locomotion. It would therefore be predicted to slow down, since less energy is available to power forward movement. Otherwise, there would be an increase in the rate of work (power) done in order to maintain speed. Conversely, downhill locomotion feeds power into the system which should enable a power limited horse to move faster.

We hypothesise that racehorses that compete in races lasting several minutes (equivalent to human milers), operate at constant power, trading off the metabolic work of forward locomotion with potential energy work. We propose that horses should run faster on downhill sections and slower on uphill sections in a manner concomitant with the energetic benefit / detriment of the potential energy power. The slope of the speed-incline relationship should be accounted for by the relative costs of forward locomotion and potential energy gain which can be evaluated by examination of VO₂ data for incline locomotion at a range of speeds on a treadmill.

**Materials and Methods**

**Dataset**

Data were taken from a dataset of racehorse speed and position recorded during racing on an undulating racetrack in the UK (Goodwood). Recordings were made during actual competition races in 2006, providing the opportunity to observe close to maximal effort, although this did preclude detailed measurement of the individuals used. A contour map of the racecourse is shown in Figure 1. Data were collected using a proprietary radio tracking system developed by TurfTrax Racing Data Ltd, described and characterized in Spence et al. (27). An emitting tag is placed in the saddle cloth of all horses in a race, and position and speed are determined at 4Hz and filtered to 1Hz. The system position accuracy is ±0.11 m (fore-aft), ±0.64 m (lateral) and speed to within ±0.15 ms⁻¹. Speed as reported here is the 2D output of a Kalman filter operating on raw 4 Hz tracking data to produce more accurate 1 Hz speed estimates. The details of this filter are proprietary, but have been optimised to produce speeds that match official finish times to a sufficient standard that they are reliable for in-race...
betting. The accuracy reported above comes from our own validation of the system through comparison with survey standard GPS. The two systems were rigidly coupled, attached to a quad bike and driven round a racetrack at speeds and accelerations comparable to the dynamics of horses (27). The GPS system against which the TurfTrax system was validated, given the typical number of satellites in view, and the type of receiver and antenna used, had an expected accuracy on the order of ± 0.02 m in position and ± 0.03 m/s in speed (manufacturer’s specification, Novatel OEM4). The track was surveyed to a 10 m grid using RTK GPS, supplemented by Total Station measurements. The track surveys were to an absolute accuracy (systematic errors less) of 0.05-0.10 m in the XY plane and of the same order in altitude.

Analysis
A 3D map of Goodwood was created in MATLAB (The Mathworks, Natick, MA, USA.) using the GPS surveys. Speed and position data from 33 races, of distances between 1006m (five Furlongs, approximately 1 minute) and 3218m (2 Miles, approximately 4.5 minutes), were then analysed using custom scripts in MATLAB. The races start in the positions indicated in Figure 1 and all finish in the same position in front of the grandstand. Data from the course survey was used to determine gradient at each horse 2D position fix. Two-dimensional racehorse position throughout the race was interpolated using track data to get vertical height data for individual horses. This height data was smoothed using a Butterworth filter (3rd order, cutoff 0.6) and then used to calculate gradient. Speeds under 13.5 ms⁻¹ were eliminated as representing submaximal effort or the acceleration and deceleration at the beginning and end of the race. Data were colour-coded relative to percentage of race completed and plotted to examine for other factors which could confound changes in speed with gradient, for instance, fatigue and race tactics. It is possible, for example, that horses may speed up at the end of the race for a sprint finish or slow down due to fatigue.

Speed data were separated into gradient bins, separated by increments of 0.5%, and the top speeds within each bin were analysed. To avoid pseudoreplication in the statistical analysis, the mean of the top 10% of speed samples for each horse, in each bin, was used. A mean for each gradient bin was then calculated and the bin means used to produce regression lines so that individual horses were represented equally.
Comparison with metabolic data

To ascertain whether speed at different gradients could be attributed to the increased metabolic cost of moving up an incline, data were compared to those of Eaton et al. (1995)(4). That study determined metabolic cost with both speed and incline in five thoroughbred horses. First, we used these data to calculate the additional metabolic cost for performing the additional mechanical work of moving up an incline (over and above the cost of galloping at the same speed on the flat). Second, we used the speeds achieved at different inclines for a constant metabolic cost in the data by Eaton et al. to produce a regression line which we could compare to our own data to investigate whether the same speed / incline relationship exists.

Results

Dataset analysis

Analysis of the Turftrax data for 33 races (373 horses) on Goodwood racetrack showed that racehorse maximum speeds were lower on both incline and decline, and that greatest speeds were achieved during level running. As specific inclines are only encountered at specific times throughout the race, incline is strongly correlated to percentage of race complete (<0.01) and we were unable to control for this in a mixed model. Figure 2 shows speed (ms\(^{-1}\)) vs gradient for all horses. The plot shows that maximum speeds of 20ms\(^{-1}\) were achieved on the level and a maximum speed of around 16ms\(^{-1}\) on a 6% incline, a decrease of 20%. Speeds were also lower on the decline with a maximum of 16 ms\(^{-1}\) on a 6% downhill slope.

Separate lines were fitted to incline and decline data using only the top 10% of speed data in each bin, since speed shows a clear inflection at 0% gradient. We ensured no horse was over represented by deriving one point per horse per incline bin by averaging all qualifying values for that horse. Linear regression lines were fitted to the means in MATLAB (using ‘regress’). The gradients of the resultant lines were 0.68 ms\(^{-1}\)/1% gradient for the decline data and -0.45 ms\(^{-1}\)/1% gradient for incline data. Corresponding \(r^2\) values were 0.97 for decline data and 0.92 for incline data. The regression lines are presented in Figure 3.

Comparison with metabolic data

Moving up a 10% incline at 8ms\(^{-1}\) (ie. 0.8ms\(^{-1}\) vertical velocity) equates to 8 Wkg\(^{-1}\) or 480 Jkg\(^{-1}\)min\(^{-1}\) potential energy power. Eaton et al., report a linear increase in metabolic rate with incline which gives a difference of approximately 70 mlkg\(^{-1}\)min\(^{-1}\) O\(_2\) between 8 ms\(^{-1}\) level
running and 8ms\(^{-1}\) on a 10% incline. Taking 1ml O\(_2\) to be equivalent to 20J metabolic energy (5) and a vertical efficiency of 35% (which is derived from a metabolic cost of ascent of 1.379ml O\(_2\) km\(^{-1}\) (31), equating to 27.6J (if 1ml O\(_2\) = 20J) and hence efficiency is 9.81J/27.7J (8)), this increase in oxygen consumption equates to mechanical (potential) energy power of 490 Jkg\(^{-1}\)min\(^{-1}\) or 8.2 Wkg\(^{-1}\). Other studies report efficiencies of about 35% for the additional cost of potential energy work compared to level locomotion in large animals (24, 26). Efficiencies are lower in smaller animals (29) but those values are of little relevance here. The increase in metabolic rate is consistent with the additional mechanical power required to increase the potential energy of the centre of mass across a range of gradients. Shortcomings in this concept are discussed below.

We compared the change in speed with gradient at constant metabolic cost, shown by Eaton et al., with our own data. We used figure 1A of Eaton et al. to calculate mean horse speed on each incline at a constant VO\(_2\) of 120 ml kg min\(^{-1}\). We assumed this represented an equivalent level of effort for these experimental horses, of lesser athletic capacity, and used these values to derive a relationship between gradient and speed (Figure 4). The resultant regression line fitted to data from Eaton et al. has a gradient of -0.49 ms\(^{-1}\)/1% gradient.

**Discussion**

The aim of this study was to explore whether a constant metabolic power limit accounts for the speed of racehorses during racing. If predominantly limited by power, racehorse maximum speed would be lower on an incline and greater on a decline. Results show that highest speeds were in fact achieved on a level gradient and horses were slower on both incline and decline slopes.

Incline data were consistent with a simple metabolic power limit. As gradient is increased, there is an increased power requirement in order to raise the COM against gravity, increasing the COM potential energy. This can be demonstrated as an energy constraint as work of forward locomotion is offset against potential energy work, as reflected in data by Eaton et al. (4). This, in turn, reflects the metabolic capacity of the animal through its ability to maintain speed on an incline. This can be utilised in the racing industry, in that, if horse speed decreases on an incline, those with the metabolic capacity to cope with the additional cost and maintain speed will take advantage over hilly races.
Comparison of the cost of horizontal movement with vertical work in humans and horses can give insight into power constraints on running. Snyder and Carello (26) combined data from a number of studies to examine the additional metabolic cost of incline running in a range of bipeds and quadrupeds of different sizes. They concluded that, although there is a substantial difference between small and large animals, in the size range we are discussing here, the efficiency of generating potential energy work from metabolic work (over and above horizontal running) is approximately constant. This means that differences in body mass do not confound conclusions about the effect of incline, for these animals. From the data in Figure 4, horses gallop 0.5ms\(^{-1}\) slower for each 1% increment in uphill gradient. From these data a horse ascending at 1ms\(^{-1}\) vertically will gallop 3ms\(^{-1}\) slower than on the flat (18ms\(^{-1}\) on the flat vs 15 ms\(^{-1}\) on a 6% slope). This equates to a trade-off of 1 vertical metre to 3 horizontal metres. Davies (2) gives a slowing of 3.3% for each 1% increase in gradient for elite human runners, a figure that is often quoted in the athletics performance literature with some anecdotal validation. At a workload equivalent to 4 minute mile pace (6.7 ms\(^{-1}\)) a runner on a 6% slope will slow by 19.8% ie. by 0.198 * 6.7 = 1.33 ms\(^{-1}\) and have a vertical velocity of 0.06 * (6.7-1.33) = 0.32ms\(^{-1}\). So for each 1m of vertical ascent they will travel 1.33/0.32 = 4.2 metres less horizontal distance. This relationship is predicted from limited data for human running which may affect accuracy. This is interesting because published data indicate that COT (energy to move 1kg 1 meter) is almost speed independent. Furthermore the COT is about twice as high in humans (5Jkg\(^{-1}\)m\(^{-1}\)(30), 4.25 Jkg\(^{-1}\)m\(^{-1}\)(6)) than horses (2.4 Jkg\(^{-1}\)m\(^{-1}\) (14), 2.44 – 2.48 Jkg\(^{-1}\)m\(^{-1}\) (31)). If the cost of doing potential energy work is similar in both then the horse should slow by twice as much as the human, because this additional cost is a much larger fraction of the total cost of transport. To the contrary, we find that the horse actually slows slightly less than the human. There are a number of potential explanations for this, including the gradients used, the accuracy of the various data sets (particularly the effect of gradient on human running speed) and differences between overground and treadmill locomotion. If horses are more efficient at performing potential energy work this may reflect an effect of the greater aerodynamic drag losses at their higher speeds, an inherent difference in their muscle efficiency or a locomotor mechanics effect.

With regard to aerodynamic drag, at racing speeds for humans (6.7 m/s) and horses (15m/s), the contribution of drag to COT is actually similar for both species: 0.26 Jkg\(^{-1}\)m\(^{-1}\) for horses (1/2 C\(_D\) rho A v\(^2\)/bodyweight, where C\(_D\) = 0.9, rho = 1.29, A = 1) and 0.33 Jkg\(^{-1}\)m\(^{-1}\) for humans (horse = 500kg, human = 80kg). So aerodynamic drag does not account for the
difference. Muscle efficiency may account for some of the difference but Snyder and Carello’s data (26) would suggest this is not the primary mechanism. Other things being equal, an animal with more efficient muscle would be able to reduce metabolic demand of incline running compared to an animal with less efficient muscle. The effect on incline running might be more than the effect on level running because the muscles are perhaps doing little net work in level running. Hence, there could be an extra advantage to efficiency in larger animals. Horses may also slow down less than humans on a slope because they are better at redirecting energy "wasted" on the level into doing work against gravity. An example of such a mechanism would be that during level running work is done against gravity at push off and then dissipated on landing. When on an incline, some of this energy might not be dissipated as the height decrease would be reduced compared to level running. The potential mechanisms associated with this are beyond the scope of this paper but would contribute to a higher than expected “vertical efficiency” (11).

Even at a muscle level there are issues with calculating the “vertical efficiency” ie. subtracting the energy cost of an isometric contraction from the energy cost of a working contraction and then calculating the efficiency as [work/(extra energy used)]. This is because the underlying assumption here is that the processes occurring in the isometric contraction occur also in the working contraction and the work is done by additional processes that occur only in the working contraction. In the isometric contraction, crossbridges form and break without much work being done. This process does not continue in a working contraction, instead the crossbridge cycles end after work has been done (39). An extreme example is cardiac muscle where the total energy output in a twitch is independent of whether or not work is done (7). So a calculation of efficiency for cardiac muscle would give a value of infinity. The error is less in skeletal muscle because in skeletal muscle there are extra crossbridge cycles in the working contractions above those in the isometrics (Fenn effect (23)), but one still cannot subtract the crossbridge cycles which happened in isometric contraction. To do so would assume that there is a cost of tension production which has to be met in addition to, and separate from, the cost of doing work. Force is not energy, not energetically constrained and it can come as a by-product of even a perfectly efficient crossbridge cycle. In locomotion the equivalent question is whether we can identify (and measure the cost of) some muscle activities that are the same during level locomotion and incline locomotion. It is likely that, during incline running, some muscles contract less isometrically than they did on the level, and therefore use more energy (Fenn effect).
subtraction of level running will however tend to give a wrong (higher) efficiency just as with isolated muscle.

Unlike in human athletes, horse speed decreased on downhill sections, indicating that downhill speed is limited by factors other than general energy supply as shown in (12). Possible explanations include an increased proportion of total weight support being undertaken by the front legs (the opposite is reported for incline locomotion (3)) requiring a higher duty factor and hence slower speed. This increase in limb impulse requirement and a peak limb force constraint accounts for horses slowing on bends due to increased effective gravity (28). A 10% decline is expected to increase the proportion of weight supported by the forelimbs by 5% if it is the inverse of the change during incline locomotion from (3). A 5% increase in the proportion of weight support by the forelimbs would result in a proportional increase in duty factor (38) if peak limb force is to remain the same (28). Assuming the equivalent effect on a decline and taking the duty factor-speed relationship of (37), this would result in a speed reduction of approximately 1ms⁻¹ from an initial speed of 18ms⁻¹. This is much less than the decrease in speed we observed so it is unlikely to be the primary factor.

Differences in morphology between horses and humans may explain the horse’s large decrease in speed on declines. When running downhill, the leg must shorten through stance to absorb potential energy. Here we use the term leg to mean the link from the foot to the centre of mass, so a hip joint flexion in a horse would appear as compression of the support limb. Leg shortening under load is easy for human athletes due to the powerful knee extensors that can undergo active lengthening. The absolute maximum speed of humans is also higher on a decline (32) which could be accounted for by their extensor muscles being stronger in lengthening contractions. The horse forelimb is highly specialised for weight support to the extent that elastic shortening and recoil can occur without muscular activity (13, 35) and the leg will buckle and swing forward when loaded late in stance (36). It is therefore possible that when galloping downhill the foreleg is poorly arranged to perform negative work due to the reduced capacity of the many short-fibred, support muscles to absorb the additional energy from moving downhill, so that the hind legs must perform the work. Furthermore, the fixed relationship between leg length and force may mean that front leg weight support is reduced on steep gradients, reducing speed. It would be interesting to measure stance times on decline sections during racing to explore this proposal: it has been shown that duty factor increases on an incline as stance time remains the same while stride frequency increases (19). The
available muscle mass may also limit hindlimb negative work as most muscles are arranged for hip torques acceleration (20, 21, 34).

The regression line of the speed against incline in this study lies above the model line from Eaton et al (see Figure 4). However, the importance lies in the similarity of the gradients of the two lines, which supports the theory of constant metabolic effort, proposed above. Differences between the two datasets are likely due to the differences in the animal subjects. The data by Eaton et al. were derived from experimental horses that are likely to have a lower VO₂max than fit racehorses and so achieve lower speeds. This reduced performance capacity could be attributed to lower metabolic capacity and / or motivation. The similarity of slope in the speed-incline plot supports the former mechanism since a less efficient horse would still slow down at a rate consistent with a constant metabolic effort.

Knowledge of limits to performance in racehorses may be used to improve training regimes. A mechanical limit to speed is likely to predominate on decline gradients, suggesting there is no potential for training for speed on downhill gradients, as already practiced in training of human athletes. If this is in fact the result of a limit to peak limb force on the forelimbs, due to a change in the front-back weight distribution, training on a decline may help improve performance through targeting specific muscles involved. However, if the limit is on inherent limb mechanics, as opposed to muscle and tendon capacity, then decline training would not help and may even cause damage and injury. This limit may vary amongst individuals and, if not a ‘trainable’ trait, may be useful in identifying individuals that can gallop faster on a decline. It would be valuable to study horses that are good and bad at downhill running to separate different limits to maximum running speed. Moreover, the clear metabolic limit to incline running further supports the need for training on the incline as already practised.

**Conclusion**

During moderate duration races, horses show a speed detriment on inclines that corresponds to trading off the metabolic cost of height gain with the metabolic cost of horizontal galloping. This is consistent with existing data for human runners. From the literature, humans run faster on a decline, explained by the energy gained by the COM from height loss, but this study has shown that horses go slower, which may be attributable to the anatomical simplicity of their front legs, limiting weight support and stability. Humans appear to be power limited with an optimum gradient of 0.1-0.2 decline for maximum speed running (15,
During racing, horse maximum speed is less on both inclines and declines, with top speeds being achieved during level running.

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References


**Figure 1.** Contour plot of Goodwood racecourse. Figure shows racetrack overlaid onto a contour plot from GPS survey. Colour represents vertical height while spacing of the contour lines indicates gradient. Race start positions for races of different lengths (in miles and furlongs) are indicated, with all races finishing at the same point in front of the grandstand. 1 furlong is approximately equal to 201m.

**Figure 2.** Racehorse speeds at different gradients during racing on Goodwood racecourse for 33 race starts (373 horses). Colour represents percentage of race complete (current time point (s)/total race time(s)). Figure shows a decrease in speed on both inclines and declines during racing.

**Figure 3.** Regression lines derived from Figure 1, showing average top racehorse speeds at different gradients during racing. Lines are fitted to the mean of the top 10% of speeds, with horses being represented equally. Error bars represent the SEM.

**Figure 4.** Regression line for incline data from Figure 3 shown with Regression line derived from data by Eaton *et al.* 1995. Figure shows comparison between speed data from this study and metabolic data from a previous study in relation to incline gradients. Similarity of the gradients of these two lines supports the theory of constant metabolic effort.
Gradient (downhill)

\[ y = 68.7x + 18.9 \]
\[ r^2 = 0.966 \]

Gradient (uphill)

\[ y = -45.3x + 17.9 \]
\[ r^2 = 0.924 \]
Goodwood data

\[ y = -45.3x + 17.9 \]
\[ r^2 = 0.924 \]

Eaton et al. data

\[ y = -48.8x + 12.9 \]
\[ r^2 = 0.988 \]