EXTERNAL MECHANICAL WORK IN THE GALLOPING RACEHORSE

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ABSTRACT

Horse locomotion is remarkably economical. Here we measure external mechanical work of the galloping horse and relate it to published measurements of metabolic cost. Seven Thoroughbred horses were galloped (ridden) over force plates, under a racing surface. Twenty-six full strides of force data were recorded and used to calculate external mechanical work of galloping. The mean sum of decrements of mechanical energy was -876J (± 280J) per stride and increments were 2163J (± 538J) per stride as horses were accelerating. Combination with published values for internal work and metabolic costs for galloping yield an apparent muscular efficiency of 37-46% for galloping which would be reduced by energy storage in leg tendons. Knowledge about external work of galloping provides further insight into the mechanics of galloping from both an evolutionary and performance standpoint.

INTRODUCTION

Like many cursors, the horse (*Equus Caballus*) has evolved to locomote economically over long distances. The horse has a very low metabolic cost of transport (1, 2) (the amount of energy consumed to cover a given distance, COT) and since domestication has been selectively bred for increased speed and endurance. Adaptive specialisations for running in the horse include a distal limb that is slim and light, with an extended, single digit and no musculature below the carpus and tarsus. The reduced weight of the distal fore and hindlimbs reduces the energy required to swing the limbs between stances (3). Further, long, elastic distal tendons allow for elastic energy storage and return (4, 5) contributing to economical locomotion (6, 7). Conversely, the proximal portions of the limbs are made up of large, bulky muscles which allow for rapid limb swinging and propulsion with the further aid of a large tendon within the biceps muscle of the forelimb which acts as a catapult to give rapid limb protraction (8).

External work in the galloping horse has been modelled (9) and measured, through kinematics (1) and inertial sensors (10) and the published values are high, 10500J (515kg at 12ms^{-1}) (1) and 8000J (480kg at 12ms^{-1}) (10) per stride, and exceed the metabolic cost of galloping. This mismatch has been attributed to energy storing springs, along with effects of skin movement, movement of the COM within the reference frame of the subject, digitising errors and sensor placement. Here we set out to make a more direct measure of external mechanical work using force plates as ergometers, as outlined elsewhere (11, 12).

MATERIALS AND METHODS

Data were collected from seven Thoroughbred racehorses at the British Racing School (BRS), Newmarket, England. All subjects were weighed on the in-house scales (477 ± 25kg) (though weights for calculations were taken as the integral of the vertical force across a stride) and limb lengths were taken to the top of the scapula (1.63 ± 0.04m) using a standard tape measure. The same professional jockey (jockey + equipment = 70.1kg) rode all horses for all trials.

Ten 0.6m x 0.9m Hall-effect force plates (AMTI custom build, Watertown, MA, USA) were placed in a custom steel frame in the racing track at the BRS on a base layer of chalk to yield a 6m x 0.9m array. Plates were covered with a membrane and protective metal/resin top-plates. Approximately 0.1m depth of oiled sand was then layered over the plates to obscure them and provide a surface over which the horses could gallop safely. The sand was smoothed between runs. The sand compacts at low force and is then relatively firm so whilst a small amount of work would be performed at foot-on, this was mostly vertical – the footprints showed no evidence of horizontal foot displacement (slipping) through stance. On the left-hand side of the track were two AOS high-speed cameras (X-Pri, AOS Technologies AG, Switzerland) set to 1280 x 560 pixels, filming at 500Hz.

Each horse was acclimatised to the setup. 3D limb force data was collected at 500Hz from the 10 plates. Each horse performed 4-6 galloping trials.

Footfall timings were taken from the high-speed video using VirtualDub (version 1.9.11), initial velocity conditions were taken from the video using custom digitisation software (13). Raw force data were analysed in a custom script written in MATLAB (The Mathworks, Natick, MA, USA.). Forces, for strides in which four complete footfalls were captured, were summed across plates with respect to time in the vertical and cranio-caudal directions. Single stride data were cut using a custom-script written in MATLAB, using stride time from the high-speed video. Integration was stopped at foot off to prevent force plate resonance giving spurious work calculations. In the majority of trials, there were simultaneous hoof contacts occurring during the stride of interest which were not on the plates and would therefore confound external work calculations. As such, the force traces for the four limb contacts were phase shifted, using stride time from the high-speed video, and over-lapped to account for these hoof contacts, under the assumption that horses were in consistent gallop and all strides were equivalent. This procedure is illustrated in the top panel of Figure 1 and in the supplementary information.

External work was calculated by summing, separately decrements (negative increments) and (positive) increments of potential and kinetic energy of the centre of mass using the series of equations as outlined in the literature (11, 12). Initial velocity conditions were taken as the average velocity across the stride from the high-speed video data and the mass of the individual was taken as the average vertical force across the stride.

Horses accelerated in every recorded stride with a submaximal mean acceleration of approximately 0.45ms^{-2}, (maximum capacity is around 3ms^{-2} (14)). This corresponds to an average net velocity increase over the stride of 0.18ms^{-1}, and a resultant increase in horizontal kinetic energy of 0.016 Jkg^{-1}. During galloping, centre of mass kinetic energy should reduce early in the stance phase of each limb (due to forward limb configuration) and such fluctuations would be ameliorated during the period of hindlimb stance by the hip torques used for acceleration. We approach the effect of the net acceleration on work calculations in two ways. One, we de-trend the acceleration by calculating the mean horizontal acceleration through the stride and subtracting that mean from the data before re-running the analysis and then calculating positive increments in external work. Two, we also sum the decrements in mechanical work in the non-detrended data. In steady state galloping, summing positive increments and summing decrements would yield the same work values, but with acceleration, the calculated work will be higher for summed increments and may be underestimated when summing decrements, because fluctuations will be reduced by the underlying upward trend. Further notes on methods can be found in the supplementary information.

RESULTS

Twenty-six complete strides were used in the analysis with speeds between 10.2ms^{-1} – 13.1ms^{-1}. In 12 of the 26 trials, the non-lead forelimb contacted the plates first.

The mean vertical displacement of the COM was 0.06m (± 0.02m) and the mean fluctuation in horizontal velocity was 0.18ms^{-1} (± 0.07ms^{-1}). The mean fluctuation (amplitude) in mechanical work was 1510J (± 479J), equivalent to 2.7Jkg^{-1}, which was reduced to 1007J in the de-trended data. The mean sum of positive increments of work was 2163J (± 538J), equivalent to 3.9Jkg^{-1} (1537J in the de-trended data), and the mean sum of decrements was -876J (± 280J), equivalent to -1.6 Jkg^{-1} (-1544J in the de-trended data). A typical plot of COM energies during one trial (one stride) is displayed in Figure 1. Data for further trials are displayed in the supplementary information.

DISCUSSION

Until now, the available data for external mechanical work in the galloping horse has been limited to calculations from kinematic data (1, 10), resulting in values for mechanical work similar to the total metabolic energy expenditure (1, 15) but much of the energy is recycled rather than dissipated and performed de-novo each stride. Muscle inital efficiency of doing mechanical work is around 20-63% (16) but this is from breakdown of existing ATP. The actual (apparent) efficiency of mechanical work determined from oxygen consumption will be considerably lower (17) but the difference has not been measured for horses. Cursorial mammals are adapted for fast and efficient locomotion (3) and explanations for this, such as energy storage in tendons (4, 6, 18) and minimising energy losses (9, 19) have been described.

Internal work was not calculated in this study but published values of 2000J per stride at 12ms^{-1} exist (1). These are approximately double the external work seen in this study when considering the decrements and close to the de-trended values. This is consistent with humans where internal work exceeds external work at higher speeds (20). The high proportion of total work being internal work reinforces the evolutionary selection pressure for light distal limbs and adaptive mechanisms for efficient locomotion.

To calculate apparent efficiency, we took the metabolic (oxygen) cost of galloping to be 2.5$Jkg^{-1}m^{-1}$ (1,21), equating to a metabolic cost of transport (for a 550kg horse) of 1375Jm^{-1}. This would result in a cost per stride (stride frequency 2.13s^{-1}, so stride length 5.63m (22)) of 7740J (at 12ms^{-1}). Taking the external work (decrements) from this study of 876J and adding internal work of 2000J per stride at 12ms^{-1}(1), gives a apparent muscular efficiency of 37%. This would require net efficiency higher than most published results for muscle (of smaller animals) which is around 25% (23). When we consider the de-trended data, this gives an apparent efficiency value of 46%. The true muscle work will be lower since energy is stored and returned by limb tendons during stance (4) and during swing (8) hence reducing muscle contributions to internal and external work. Using the example trial shown in Figure 1, we can approximate elastic strain energy from the force data, using resultant force as axial limb force and a leg stiffness value of 55kNm^{-1} (6, 7). Figure 2 shows this strain energy and the effect on total energy throughout the stride. This reduces the total positive and negative increments of work for much of the trial and shows a net positive work produced by the hindlimbs at the end of the stride.

Factoring in aerodynamic drag, at speeds of 12ms^{-1}, the contribution of drag to COT is 0.15$Jkg^{-1}m^{-1}$ ($1/2\ C_D\ \rho\ A\ v^2$/ bodyweight: $C_D = 0.9$, $\rho = 1.29kgm^{-3}$, $A = 1m^2$, 550kg mass) equivalent to around 464J per stride, which is a considerable proportion of the mechanical work being performed and will increase the cost of galloping and yield a muscle efficiency of 43% (52% for de-trended data). While often considered to be negligible, this is a larger proportion of total mechanical work than previously considered, and likely explains the importance of aerodynamic drafting in winning horse races (24) especially as it is proportional to v^2 and will be much higher at racing speeds (17-20ms^{-1}).

With regard to this study being performed on ridden horses, 13% of the total mass is the rider who, in racing posture, will add weight but limited inertia. As the rider can move horizontally somewhat out of phase with the horses COM (25), the horse can reduce the horizontal work on the rider whilst still supporting their weight. Calculating mechanical works for horse mass alone would result in an 11% increase in mass specific work.

Knowledge of the mechanics of galloping can give insight into the increase in total work as a result of perturbations which may impose a power limit to maximum speed. For example, moving up a 10% incline at 12ms^{-1} (ie. 1.2ms^{-1} vertical velocity) equates to 706Jkg^{-1}min^{-1} (12Wkg^{-1}) potential energy power, equivalent to approximately 3000J per stride (26). Given external work values from this study, galloping on a 10% incline would increase total mechanical work by over 100%, which is concomitant with the increase in metabolic cost (21, 27). Energy supply may eventually become limiting which may become apparent from measurements of maximum speed on different gradients.

Between-trial variability is somewhat high in this dataset which can be attributed to the nature of the set-up and excitability of racehorses. While every effort was made to ensure steady-state locomotion, horizontal kinetic energy increased in most strides, eg. in the stride shown in Figure 1, however, this only represents an increase in absolute velocity of 0.2ms^{-1} which may be as close to steady state as possible for overground locomotion outside of the laboratory.

CONCLUSION

Large animals are known to be uniquely economical with a low COT. Understanding of the costs and efficiency of high-speed locomotion in large cursorial animals gives insight into how they have evolved anatomically and physiologically to meet the evolutionary selective pressures that result from ranging to find resources in open grasslands and the need for high speed predator evasion. These adaptations underpin the metabolic and mechanical factors affecting and limiting athletic performance in racehorses.

The results show that external work is a small fraction of the total mechanical work of galloping, less than that of internal work and similar in magnitude to the aerodynamic drag costs. Apparent muscle efficiencies are of 37-46% and exceed net efficiencies demonstrating the importance of elastic cycling of energy in limb tendons.

Ethics

Ethical approval for this study was granted by the RVC Welfare and Ethics Committee (URN 2011 1107).

Data accessibility

Data are available from the Dryad Digital Repository doi:10.5061/dryad.db543. Further details of data analysis and additional figures have been uploaded as electronic supplementary information.

Author contributions

ZTSD, AJS and AMW designed the study, collected and analysed data and wrote and revised the manuscript. All authors approved the final manuscript and agree to be accountable for all aspects of the study.

Competing interests

The authors have no competing interests to declare

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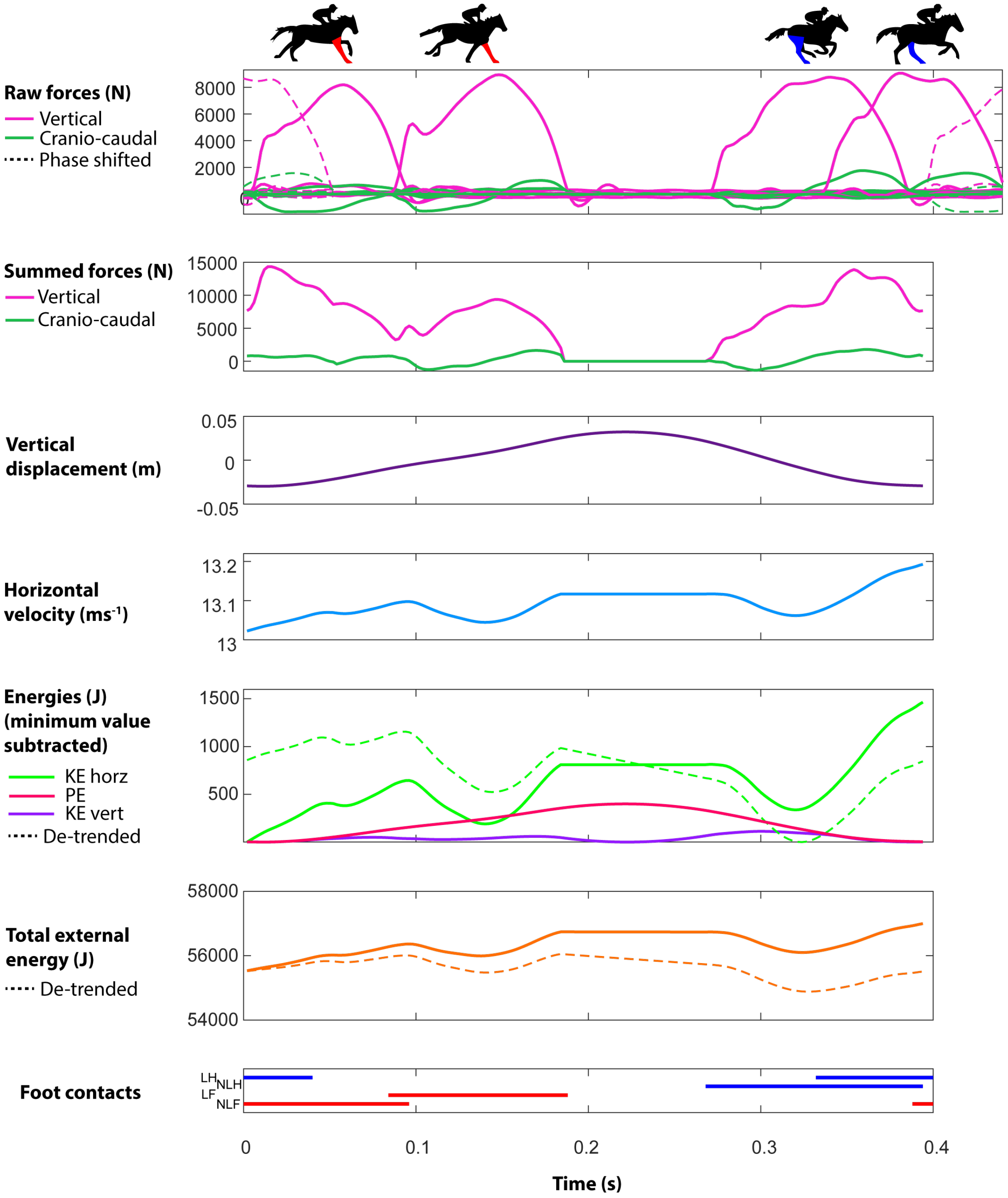

FIGURE 1. Forces and energy fluctuations during a typical galloping trial (13ms^{-1}). Top panel shows raw force data (dashed lines show phase-shifted overlay) while panel 2 shows summed force data used in the calculations. Below are vertical displacement of the COM in m and horizontal velocity throughout the stride. The 5th panel shows horizontal kinetic (dashed line shows de-trended data), potential and vertical energy fluctuations throughout the stride. Panel 6 shows the total energy fluctuations throughout the stride with the dashed line representing the de-trended values. Stance times are represented in the bottom panel, corresponding to the images at the top. Energy traces in panel 5 have had the offset of their minimum value removed.

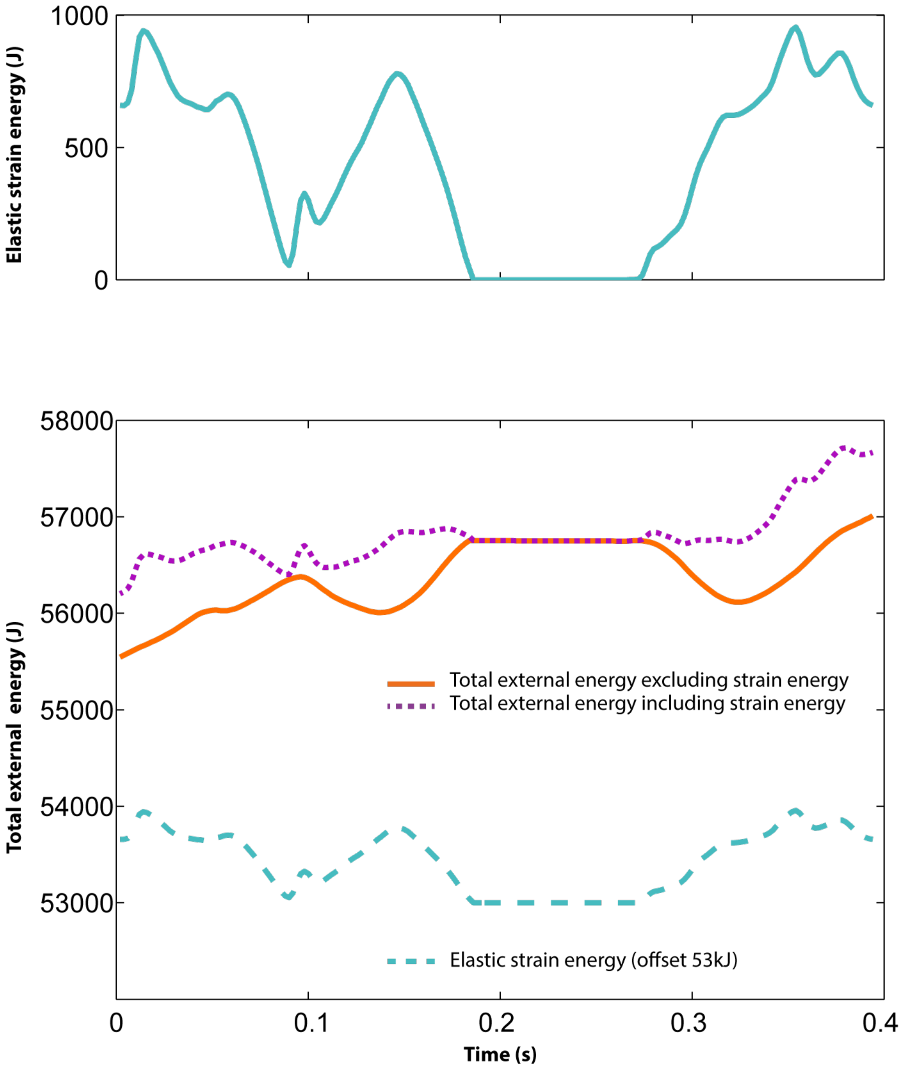

FIGURE 2. Top panel shows calculated elastic strain energy throughout one stride. Lower panel shows the effect of elastic strain energy on total energy (elastic strain energy is shown again here to scale but absolute values have been offset by 53kJ).

SUPPLEMENTARY INFORMATION

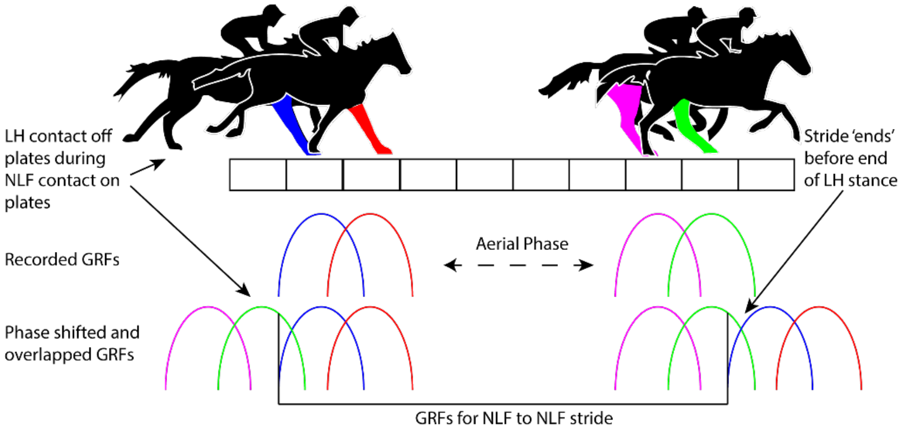

Figure 1. Diagram to show how force plate traces were phase-shifted, using stride time from high speed video, to account for footfalls occurring off the plates which would affect external work calculation. This assumes steady-state and that all strides are the same.

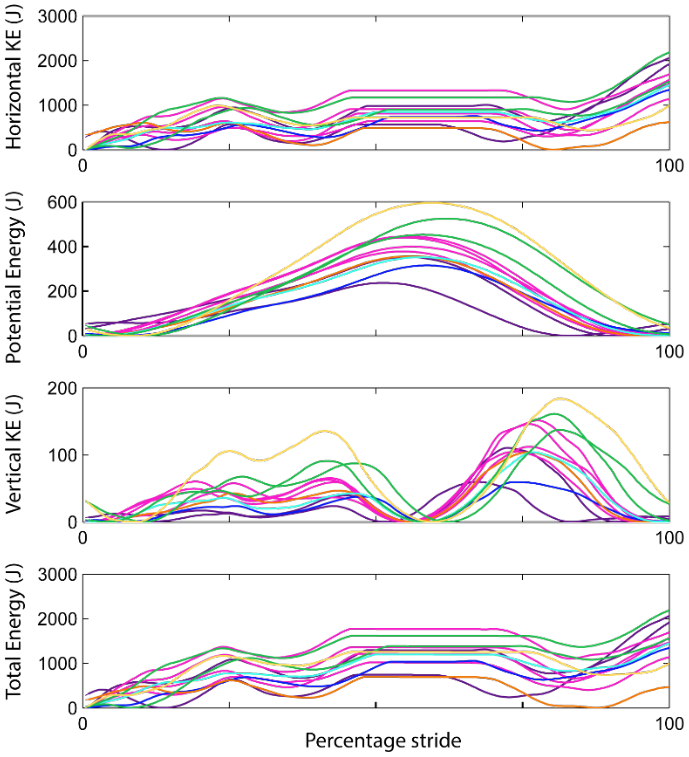

Figure 2. Overlay of energy fluctuations during a stride for 12 trials (NLF-NLF) across 7 individuals. Galloping speeds range from 10.2ms^{-1} to 13.1 ms^{-1}. Line colours represent different individuals. Energy traces have had the offset of their minimum value removed. This diagram includes the same trial as in Figure 1 of the main paper.

Notes on Materials and Methods and calculations

Video analysis:

2 AOS high-speed cameras were set back 5 m from the track, with a view of approximately 5 m before the plates and 5 m after the plates with an overlap of approximately 1 m in the middle to ensure that full strides were captured. The cameras were set to 1280 x 560 pixels and were calibrated using a 31cm calibration frame throughout the field of view. The velocity of the COM was estimated by tracking a fixed point on the horse, the girth (strap on the saddle), as this was an area of decent contrast that remained in a fixed position on the trunk of the horse. The equations used require initial velocity conditions, we used the average velocity from the video as this allowed the most accurate estimation (the velocity was taken as the average velocity across a stride since velocity is displacement over time and the shorter the time interval the greater the effect of any errors in measurement of displacement.)

Aerodynamic drag:

Here we considered the horse and jockey to be a bluff body and in comparison with a bicyclist with known Cd of 0.9. This is somewhat conservative and, as with the other calculations in the discussion, this is an assumption. The aim was to give an idea of the proportion of mechanical work that is drag.

Efficiency calculation:

Efficiency defines the ratio of how much mechanical work is performed for a given amount of metabolic work and relates to the efficiency of the locomotor muscles.
Efficiency = (external mechanical work + internal mechanical work)/metabolic cost
Here we use our measured value for external work of 876J (we used the decrements value here as this is most conservative) and values from the literature for internal work and metabolic cost.
We take the internal work value from Minetti et al. for an equivalent speed of 2000J. This value is approximated from Figure 4 of the paper which shows an internal work value of approximately 0.7$Jkg^{-1}m^{-1}$ (the horses in the study were around 500kg, and the stride length of a horse at 12ms^{-1} is around 6m). To give an idea of range and sensitivity of this calculation, we present the effect here of varying these values as this value is based on a number of assumptions (we are estimating stride length, horse mass and reading from a figure). If we consider the internal work value to range between 0.7$Jkg^{-1}m^{-1}$ and 0.8$Jkg^{-1}m^{-1}$, stride length to range between 5-6m and horse mass to range between 500-550kg, this gives us a range of internal work values: 1750-2640J. This would give a range of efficiency values of 34-45%.
These calculations are made as discussion points for the reader to take at whatever level they wish.