Effect of speed on stride parameters in racehorses at gallop in field conditions

T. H. Witte[1],*, C. V. Hirst[1],† and A. M. Wilson[1,2],‡

[1]*Structure and Motion Laboratory, The Royal Veterinary College, Hawkshead Lane, Hatfield, Hertfordshire, AL9 7TA, UK and [2]Structure and Motion Laboratory, University College London, Royal National Orthopaedic Hospital, Brockley Hill, Stanmore, Middlesex HA7 4LP, UK*

*Present address: Cornell University Hospital for Animals, Box 25, Ithaca, NY, 14853, USA
†Present address: 25 Lodge Hill Road, Lower Bourne, Farnham, Surrey GU10 3QW, UK
‡Author for correspondence at address 1 (e-mail: awilson@rvc.ac.uk)

Summary

Stride duration, stance duration and protraction duration are key variables when describing the gaits of terrestrial animals. Together, they determine the duty factor (the fraction of the stride for which the limb maintains contact with the ground surface), from which the peak vertical force can be estimated. When an animal changes speed, these variables change at different proportions. Limited measurements of these variables and predictions of peak limb force have been undertaken for large mammals performing high-speed over-ground exercise. This study set out to make such measurements, employing a previously validated system consisting of limb-mounted accelerometers and a Global Positioning System data logger. Measurements were made on nine elite Thoroughbred racehorses during gallop locomotion over a range of speeds from 9 to 17 m s^{-1}. No statistically significant differences were seen in any variables between the lead and non-lead limbs for either the fore or hind pairs of limbs. Mean stance durations of 131 and 77 ms in the forelimbs and 143 and 94 ms in the hindlimbs were recorded at speeds of 9 and 17 ms^{-1}, respectively. Equivalent values for protraction duration were 364 and 342 (fore) and 355 and 326 ms (hind). Peak limb forces (from duty factor) at 17 ms^{-1} were 24.7 N kg^{-1} body weight (range 22.6 to 26.0 N kg^{-1} body weight) for the forelimbs and 15.3 N kg^{-1} (range 13.7–16.2 N kg^{-1} body weight) for the hindlimbs. The duration of the aerial phase of the stride (when no limbs are in contact with the ground) was independent of speed. Overlap time (when more than one leg is on the ground) dropped with speed and approached zero at maximum speed.

Key words: biomechanics, locomotion, horse, duty factor, speed, gallop, equine.

Introduction

The top speeds achieved by a wide variety of cursorial quadrupedal animals from the hare to the horse are surprisingly similar, despite a 100-fold range in body mass (Garland, Jr, 1983). All of these animals attain their top speed (40 mph) with a similar minimum duty factor (0.2) and hence similar peak vertical force (approximately 2× body weight). Although the determinants of maximum running speed have been examined in detail in human athletes, who can achieve speeds approximately half as fast (Weyand et al., 2000; Usherwood and Wilson, 2006), and in dogs (Usherwood and Wilson, 2005), similar studies of large galloping quadrupeds are sparse. This study therefore set out to describe in detail the stride parameters of a group of elite racehorses performing high-speed over-ground locomotion.

Elongated limbs should enable an athlete to achieve longer stance times and take longer strides, and slender limbs combined with fast muscle fibres should allow for more rapid repositioning of the limbs during the protraction phase and hence higher stride frequencies. However, longer limbs do not automatically result in longer strides (Armstrong and Cooksey, 1983) and protraction duration is unlikely to be greatly affected by muscle fibre speed, given that limb protraction is, at least in horses, a largely passive process, achieved through elastic recoil rather than active muscle work (Heglund et al., 1982; Wilson et al., 2003).

In humans, minimum protraction duration is the same regardless of subject ability and within a subject, protraction duration is the same during declined and inclined running, even though the maximum speed is markedly different. Maximum attainable limb force, on the other hand, is significantly higher in fast *versus* slow runners and is higher for declined *versus* inclined running. Therefore, humans achieve faster top running speeds with greater peak vertical ground reaction forces rather than more rapid leg movements (Weyand et al., 2000). This is not true for greyhounds (Usherwood and Wilson, 2005) and may not be true for large quadrupeds.

Direct measurement of ground reaction force during high-

speed locomotion in large animals is extremely difficult. Force measuring treadmills have been used in horses (Weishaupt et al., 2002) but treadmill gait is not completely normal and it would be difficult to study fit top class racehorses at their maximum attainable speed in that environment. Force shoes have been used in horses with some success (Björk, 1958; Frederick, Jr and Henderson, 1970; Hugelshofer, 1982; Kai et al., 2000; Ratzlaff et al., 1985; Ratzlaff et al., 1990; Roepstorff and Drevemo, 1993) but their mass and size may influence locomotion. The linear relationship between metacarpophalangeal joint extension angle and vertical limb force can be used (McGuigan and Wilson, 2003); however, this requires the collection of optical motion capture data, which is very difficult for more than a few strides under field conditions due to the resolution required for accurate angle measurements and the protective boots worn by exercising horses.

As the speed of a running animal increases, the duration of the protraction phase remains relatively constant (Pratt and O'Conner, 1978), but stance time drops resulting in an increase in stride frequency. The impulse applied to the animal's centre of mass must remain constant for a given stride duration, therefore knowledge of the duty factor (the fraction of the stride for which the limb is in stance) provides the basis for the prediction of peak limb force during high-speed over-ground locomotion (Alexander et al., 1979; Witte et al., 2004). This technique remains the easiest means of investigating the relationship between limb force and running speed in all four limbs of large animals during real-life activities. Stride timing variables (stance duration and stride duration) can be measured in the horse using foot-mounted accelerometers, which have been shown to be accurate to within 2.3 ms and 3.5 ms for the timing of foot-on and foot-off, respectively (Witte et al., 2004). The force estimated using this method is most accurate for animals performing symmetrical gaits, such as trotting, where trunk mass is distributed evenly between a pair of limbs. It may be less accurate, however, for the asymmetrical gaits, where the assumption that paired legs apply the same impulse is not necessarily true (Minetti, 1998; Witte et al., 2004).

When travelling at high speeds, quadrupeds switch from symmetrical gaits, where the footfalls of a pair of limbs (fore- or hind-) are evenly spaced in time, to asymmetrical gaits, such as galloping, where the two limbs of a pair strike the ground in couplets (Hildebrand, 1989). These gaits are analogous to a child skipping, and indeed a galloping horse has been likened to two skipping bipeds linked by a trunk (Minetti, 1998). The first limb of a couplet to strike the ground is known as the non-lead limb and the second the lead limb. For the forelimbs this means that the lead limb is the last leg to leave the ground before the aerial, or flight, phase during which there are no limbs in contact with the ground. The sequence of footfalls is therefore non-lead hindlimb, lead hindlimb, non-lead forelimb and finally lead forelimb prior to the aerial phase (Fig. 1). This sequence means that the function of the four individual limbs of a galloping quadruped cannot be assumed to be equivalent. The ground reaction force experienced by the non-lead limb at a slow canter is
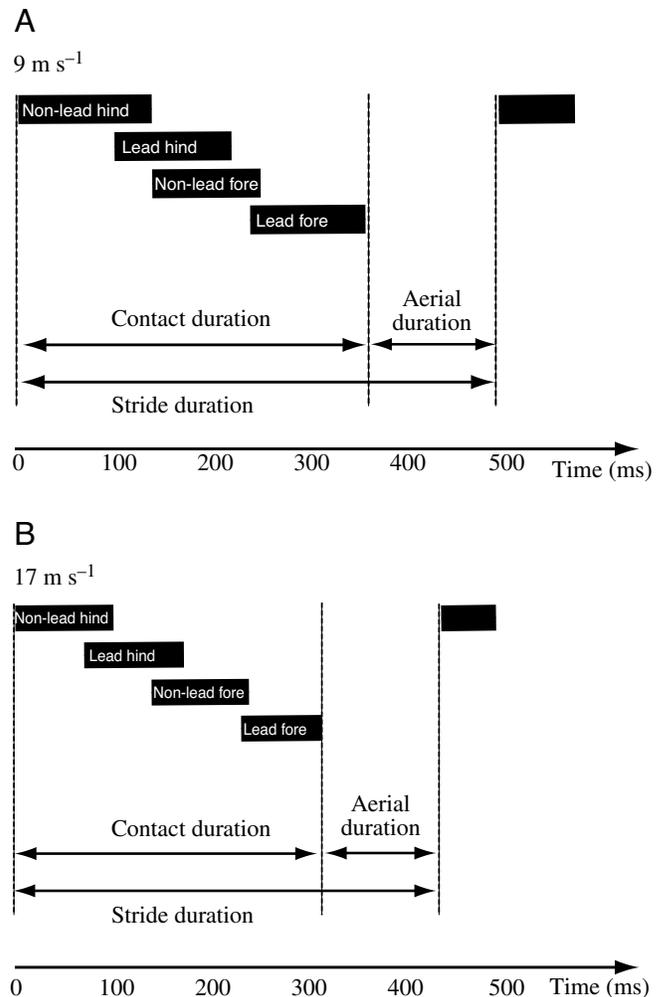

Fig. 1. The sequence of stance phases drawn to scale for all four limbs of a galloping horse. One stride is shown at (A) 9 m s^{-1} and (B) 17 m s^{-1}, drawn using the mean data from the six horses where a full data set existed for all four legs.

25% higher than that of the lead limb, although this difference declines toward symmetry with increasing speed (Witte et al., 2004). However, the effect of speed on the stance duration of the lead and non-lead limbs of a galloping horse is unknown. As speed increases, the degree of overlap between the limb stance phases decreases until the gait takes on a true four-beat rhythm, with the lead and non-lead limbs functioning almost independently. The degree of overlap between the stance phases of a pair of limbs has been proposed to be a predictor of potential racing performance and injury risk in Thoroughbred racehorses (Pratt and O'Conner, 1978). The ratio of forelimb to hindlimb impulses is 57:43 (Merkens et al., 1991) or 56:44 (Merkens et al., 1993) during ridden canter and this ratio has been shown to be independent of speed and gait across walk, trot and canter in unridden horses (Witte et al., 2004). However, the ratio of peak forces decreased slightly over a range of speeds at trot and led canter.

This study set out to examine the speed dependence of fore-

and hindlimb duty factor and predicted limb force during high-speed locomotion in the fit racehorse.

Materials and methods

Data collection

Nine clinically sound Thoroughbred racehorses of mean age 2.9 years (range 2–5 years), mean mass 476 kg (range 460–500 kg) and mean height 1.62 m (range 1.59–1.67 m) were used in the study. The animals were stabled at a single yard, were all undergoing the same regime of race training and were close to race fitness. Prior to kinematic assessment the height of each horse was measured at the fourth thoracic vertebra using a standard height stick and the mass measured using standard equine scales. The mass of the jockey and riding equipment was 63.5 kg.

Each horse was equipped with four foot-mounted accelerometers and the jockey with a stand-alone GPS data logger. A ±50 g accelerometer (ADXL150, Analog Devices, USA) was mounted on the dorsal midline of each hoof, ensuring that the sensitive axis of the sensor was orientated axially (Witte et al., 2004). Data were telemetered *via* a narrow band FM telemetry transmitter (ST500, Wood and Douglas Ltd, Tadley, UK), which was secured with a battery to the lateral aspect of the third metacarpal/metatarsal bone within an elasticated exercise bandage (Fig. 2). The data were received
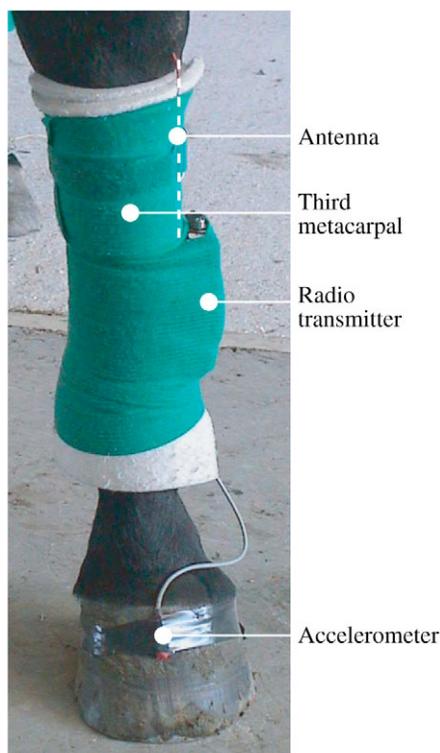

Fig. 2. Hoof-mounted accelerometer and telemetry unit, antenna and battery mounted in an elasticated exercise bandage on the lateral aspect of the third metacarpal bone.

by an SR500 telemetry receiver (Wood and Douglas Ltd) and were logged *via* a 12-bit A/D converter and PCMCIA card (DAQcard700, National Instruments, Newbury, UK) into a laptop computer running custom software written in MATLAB (The Mathworks, Natick, MA, USA). The accelerometer output file was time-stamped to allow for subsequent synchronisation with the GPS unit. The telemetry receivers and laptop computers were placed in a vehicle, which was driven round the inside of the track level with the horses as they were galloping. The receivers therefore stayed within range for the duration of data collection.

A self-contained GPS data logger (modified G30-L, Laipac Technology Inc., Ontario, Canada) was configured to log the minimum recommended GPS data (GPRMC) i.e. speed (knots), position (latitude and longitude), time (Universal Time Constant) and date, once per second (Witte and Wilson, 2004). The device (dimensions 70 mm×50 mm×25 mm and mass 95 g) was mounted securely on the rider's hat by means of a custom-made elasticated strap and was powered on as the horses left the yard. Data were logged continuously from this time for the duration of the exercise.

The horses were also equipped with an inertial sensor, which forms the basis of another paper (Pfau et al., 2006).

The horses were ridden by their regular exercise rider during the study. They were exercised in groups of three, although data were collected from only one horse at a time. The horses were warmed up by walking and trotting for approximately 10 min on a sand based racetrack (Polytrack, Martin Collins, UK). They were then accelerated to canter over a few seconds, cantered at a steady speed for 600 m, before gradually accelerating to maximum speed over a further 400 m. Accelerometer data were collected only during canter and gallop exercise, which was approximately 2 min in duration. This encompassed the entire range of exercise speeds. Exercise duration was kept brief to ensure that the horses did not become fatigued during data collection (which could affect the results).

Data analysis

GPS data in the standard NMEA 0183 format were downloaded from the data logger using GPS Wedge Software (CommLinx Solutions Pty Ltd, Lutana, TAS, Australia). Speed and time data were extracted for each position fix using custom software written in MATLAB.

Accelerometer data were imported into data transcription software (Audio Transcriber, freeware, http://www.etca.fr/CTA/gip/Projets/Transcriber/). Features corresponding to 'foot-on' and 'foot-off' have been defined previously by comparison to force plate data (Witte et al., 2004). These features were identified and the relative timing of these events was recorded. The times of foot-on and foot-off were used to calculate stance duration, protraction duration and duty factor for each stride of each leg. Stance length was defined as the distance travelled by the trunk during the stance phase of an individual limb and was calculated as stance duration multiplied by horse velocity. Peak vertical ground reaction

force was predicted for each limb using the following equation (Alexander et al., 1979):

$$Fz_{max} = \pi pmg / 4\beta ,$$

where Fz_{max}=peak vertical ground reaction force (N), P=the relative impulse of the pair of legs in question (0.57 and 0.43, for the front and rear pairs, respectively (Witte et al., 2004), m=mass of animal (kg, including mass of jockey and tack), g=gravitational constant (9.81 m s^{-1}) and β=duty factor. Predicted forces were then normalised to body mass.

For each stride the fore- and hind-pairs of limbs were defined as lead and non-lead limbs from the relative timing of the footfalls for that pair of legs. Each limb-stride was therefore described as either 'lead' or 'non-lead'. The mid-point of each stride was determined and GPS speed was interpolated to calculate horse speed at that time.

Stride data below 8 m s^{-1} were discarded, as these speeds constituted trot locomotion and locomotion through the trot–gallop transition. In addition, low-pass filtering of speed data by the GPS receiver makes speed measurements during rapid acceleration and deceleration inaccurate (Witte and Wilson, 2004). The strides thus discarded were few in number. Data above 8 m s^{-1} were used for further analysis and categorised into 1 m s^{-1} speed bins for the calculation of means, with the labels indicating the middle of the range for each bin. The relationship of each variable to speed and the influences of 'lead' or 'non-lead' and 'fore-' or 'hind-' were examined. Influences were extracted using a general linear model with speed, lead or non-lead and fore- or hind- as fixed factors, and horse identity as a random factor, using SPSS (SPSS 12.0 for Windows, SPSS Inc., USA). Best-fit curves were estimated for each variable for both fore- and hindlimbs for each individual according to the second order polynomial function [$Y=b_0+(b_1t)+(b_2t^2)$]. A second order polynomial function was chosen as the simplest model yielding the best and most consistent fit to the variables of interest. Subsequently, these models were used to predict values in each speed category for each horse, and a population mean was determined from these data.

The duration of the aerial phase of the stride, when no limbs are in contact with the ground, was calculated as the difference between lead forelimb foot-off time and non-lead hindlimb foot-on time for each stride. The duration of contact, when there was at least one limb in contact with the ground, was therefore the difference between the stride duration and the aerial phase duration. There were no double aerial phases recorded during the study so this gave an accurate representation of the contact duration. The duration of overlap (period when two feet were on the ground) was calculated as the difference between the sum of the individual limb stance phases and the total contact duration.

Results

A total of 5642 strides was analysed (ranges: 142–919 per horse and 330–825 per speed category). The maximum speed
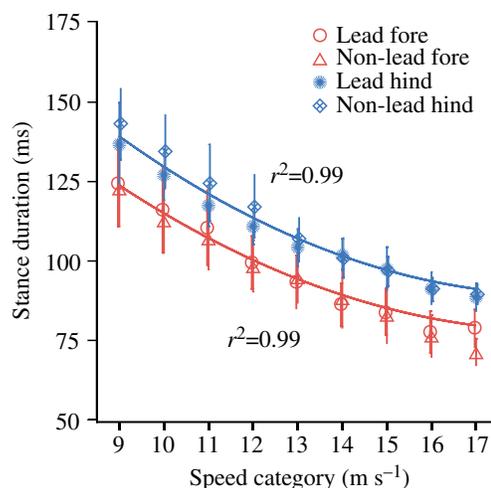

Fig. 3. Stance duration as a function of speed. Values are means ± s.d. of individual horse mean data for lead and non-lead limbs (indicated by different symbols) and fore- and hindlimbs (red and blue, respectively) for the six horses for which complete data sets were available. Quadratic lines of best fit ($P<0.001$) are shown. These were estimated for the population using mean data. Coefficients: forelimb b_0=270.33, b_1=−19.1 and b_2=0.5047; hindlimb b_0=243.56, b_1=−17.426 and b_2=0.4591.

recorded was 17.3 m s^{-1}, and all horses achieved at least 16 m s^{-1}. Due to equipment failure, complete data sets, consisting of accelerometer data for all four limbs at all speeds, were only available for six of the horses. Lead, non-lead and fore–hind relationships for the key variables were first examined in these six horses (stance and protraction durations are shown as functions of speed in Figs 3 and 4, respectively). No statistically significant differences were seen between the lead and non-lead limbs for any of the variables studied for either the fore- or hind-pairs of legs. Lead and non-lead limb data were therefore combined for further analysis, and the additional three animals for which incomplete data sets were available were included. Figs 3–9 present mean values and standard deviation (s.d.) calculated from the data for each horse in each speed bin with a 2nd order polynomial fitted through those data. The values in Table 1 are derived by fitting a 2nd order polynomial curve to the data for each horse and using these curves to determine individual horse values at 9 m s^{-1} and 17 m s^{-1} and then the means ± s.d. The different approaches used mean that the values in the graphs and the table do not match completely.

Over the speed range 9–17 m s^{-1}, stance duration decreased on average from 131 ms to 77 ms and 143 ms to 94 ms for the fore- and hind legs, respectively (Fig. 3, Table 1). Hindlimbs consistently showed significantly longer stance durations than forelimbs across the entire speed range ($P=0.003$) with no convergence or divergence at higher speeds.

Protraction duration was slightly longer in the forelimbs than in the hindlimbs at all speeds ($P=0.007$, Fig. 4). The overall population trend was a moderate, significant decrease in

Table 1. *Stride parameters*

	Speed (m s^{-1})	Forelimbs	Hindlimbs
Stance duration (ms)	9	131.4±13.9	142.8±7.8
	17	76.7±4.6	93.6±5.9
Protraction duration (ms)	9	363.9±16.0	355.0±11.1
	17	341.8±14.2	326.4±15.9
Duty factor	9	0.27±0.03	0.29±0.02
	17	0.18±0.01	0.22±0.01
Stance length (m)	9	1.18±0.14	1.28±0.10
	17	1.31±0.07	1.58±0.07
Normalised force (N kg^{-1})	9	16.8±2.1	11.7±0.4
	17	24.7±1.4	15.3±0.9

Population values are means ± s.d. at 9 m s^{-1} and 17 m s^{-1}, predicted from quadratic best-fit functions for each individual.

Fig. 5. Stride frequency as a function of speed. Values are means ± s.d. of individual horse mean data for all nine horses studied. The quadratic line of best fit (*P*<0.001) is shown, which was estimated using mean data. Coefficients: b_0=1.7052, b_1=0.0305 and b_2=0.0004.

protraction duration from 364 ms to 342 ms and 355 ms to 326 ms for fore- (*P*<0.001) and hindlimbs (*P*<0.001), respectively. A slightly greater decrease in lead forelimb protraction duration was evident at very high speed (16 and 17 m s^{-1}); however, this was not seen consistently in the individual horse data and was not statistically significant (*P*=0.67).

Stride frequency increased linearly with speed, showing no evidence of a plateau at the higher speeds (Fig. 5). At 9 m s^{-1} the mean stride frequency was 2.02 and it increased to 2.41 strides s^{-1} at 17 m s^{-1}.

Duty factor decreased curvilinearly with speed (Fig. 6). Across the entire speed range hindlimb duty factor was significantly higher than that of the forelimbs, reflecting the longer stance duration (*P*=0.004). The proportionate difference between hind- and forelimbs was consistent. The mean individual horse duty factor recorded at 17 m s^{-1} ranged from 0.170 to 0.196 m s^{-1} (mean 0.182 m s^{-1}) for the forelimbs and 0.205 to 0.246 m s^{-1} (mean 0.222 m s^{-1}) for the hindlimbs.

The difference between forelimb and hindlimb duty factor resulted in a difference in predicted peak vertical ground
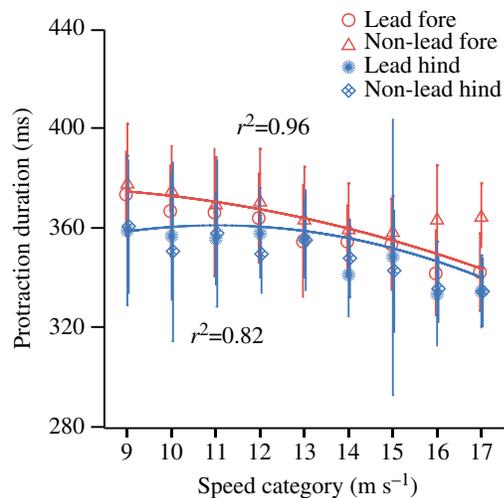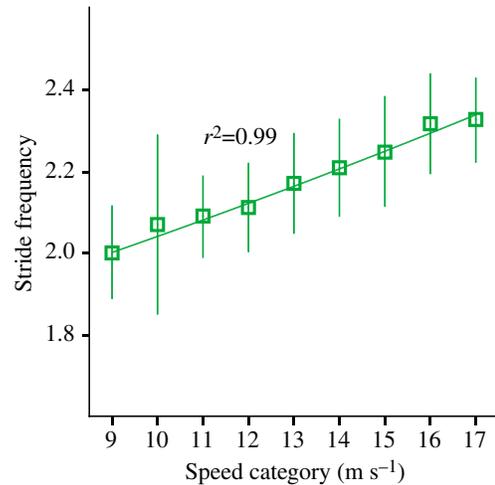

Fig. 4. Protraction duration as a function of speed. Values are means ± s.d. of individual horse mean data for lead and non-lead limbs (indicated by different symbols) and fore- and hindlimbs (red and blue, respectively) for the six horses for which complete data sets were available. Quadratic lines of best fit (*P*<0.001) are shown. These were determined for the population for fore- and hindlimbs separately using mean data. Coefficients: forelimb b_0=363.92, b_1=3.9561 and b_2=–0.3026; hindlimb b_0=288.88, b_1=13.141 and b_2=–0.5954.

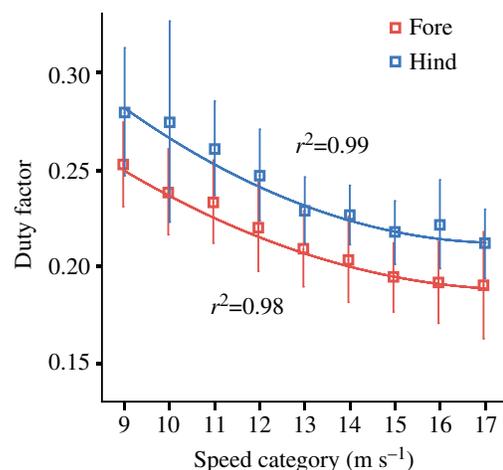Fig. 6. Duty factor as a function of speed (*N*=9). Values are means ± s.d. of individual horse mean data for fore- and hindlimbs (red and blue, respectively). Quadratic lines of best fit (*P*<0.001) are shown for the population. These were calculated for fore- and hindlimbs separately, using mean data. Coefficients: forelimb b_0=0.4334, b_1=–0.0274 and b_2=0.0008; hindlimb b_0=0.5071, b_1=–0.0339 and b_2=0.001.
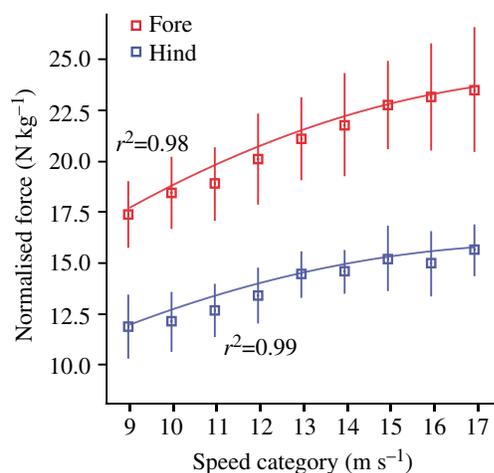
Fig. 7. Predicted peak vertical force, normalised to total mass of subject (including mass of horse, riding tack and rider) as a function of speed (*N*=9). Values are means ± s.d. of individual horse mean data for fore- and hindlimbs (red and blue, respectively). Quadratic lines of best fit (*P*<0.001) are shown for the population. These were calculated for fore- and hindlimbs separately using mean data. Coefficients: forelimb b_0=–2.778, b_1=2.1376 and b_2=–0.0535; hindlimb b_0=1.3249, b_1=1.5444 and b_2=–0.041.

reaction force (Fig. 7). Forelimb force increased by 47% and hindlimb force by 31% between speeds of 9 and 17 m s^{-1}. At 9 m s^{-1} forelimb force was 44% higher than hindlimb force and at 17 m s^{-1} it was 61% higher. The mean peak force predicted at 17 m s^{-1} was 24.7 N kg^{-1} body weight (range 22.6 to 26.0 N kg^{-1} body weight) for the forelimbs and 15.3 N kg^{-1} (range 13.7–16.2 N kg^{-1}) for the hindlimbs.
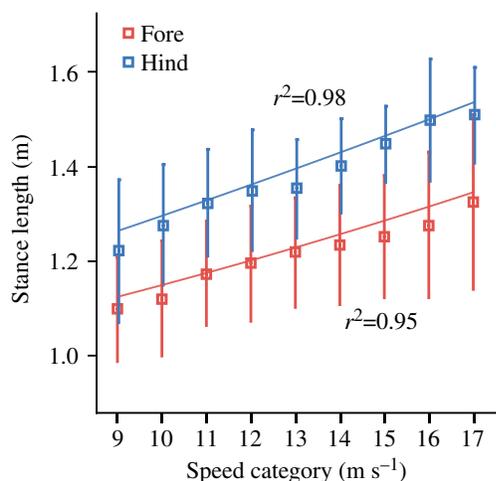

Fig. 8. Stance length as a function of speed (*N*=9). Values are means ± s.d. of individual horse mean data for fore- and hindlimbs (red and blue, respectively). Quadratic lines of best fit (*P*<0.000) are shown for the population. These were calculated for fore- and hindlimbs separately, using mean data. Coefficients: forelimb b_0=0.9385, b_1=0.0172 and b_2=0.0004; hindlimb b_0=1.0002, b_1=0.027 and b_2=0.0003.
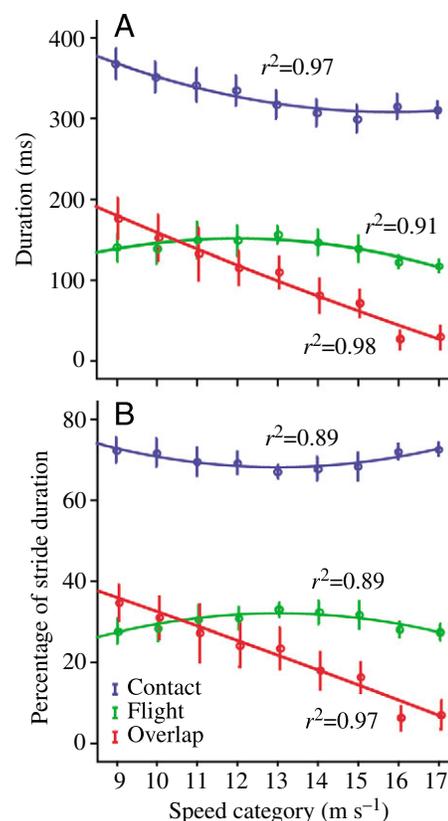

Fig. 9. (A) Total contact duration, flight duration and limb overlap duration as a function of speed. Values are means ± s.d. of individual horse mean data. Quadratic lines of best fit (*P*<0.000) are shown for the population. These were calculated using mean data. Coefficients: contact: b_0=633.89, b_1=–41.187 and b_2=1.302; flight: b_0=–55.25, b_1=34.405 and b_2=–1.4337; overlap: b_0=395.43, b_1=–26.42 and b_2=0.2757. (B) Contact, flight and limb overlap as a percentage of total stride duration as a function of speed. Quadratic lines of best fit (*P*<0.000) are shown for the population. These were estimated using mean data. Coefficients: contact: b_0=117.12, b_1=–7.5431 and b_2=0.2901; flight: b_0=–17.116, b_1=7.5431 and b_2=–0.2901; overlap: b_0=65.381, b_1=–3.1195 and b_2=–0.0215.

The distance travelled by the trunk during the stance phase (the stance length) was significantly higher in the hindlimbs than in the forelimbs across the entire speed range (1.28 m *versus* 1.18 m at 9 m s^{-1} and 1.58 m *versus* 1.31 m at 17 m s^{-1}, *P*=0.002, Fig. 8). Stance length (*SL*) can be related to half the angle swept by the limb (approximately contact angle if the sweep is symmetrical around the vertical) during the stance phase (θ) by the function θ=sin^{-1}(0.5*SL*/*LL*), where *LL*=leg length (m). Leg length was estimated assuming that the point of attachment of the scapula to the trunk was 0.1 m lower than the height of the horse and that the hindlimb and forelimb were the same length. Mean leg length was therefore 1.5 m. θ ranged from 23° at 9 m s^{-1} to 26° at 17 m s^{-1} for the forelimbs and from 25° at 9 m s^{-1} to 32° at 17 m s^{-1} for the hindlimbs.

The population mean duration of the aerial phase of the stride decreased between 9 and 17 m s^{-1} from 135 to 119 ms,

although when individual horse mean values were compared at these two speeds using univariate analysis of variance (ANOVA) within the general linear model, there was no significant difference (N=8, P=0.16). The duration of the contact phase decreased significantly from 376 to 311 ms (P<0.001) (Fig. 9A). Since there was also a concomitant decrease in stride duration (from 495 ms to 415 ms), these decreases were not apparent when the variables were expressed as percentages of the stride duration (the aerial phase remained at approximately 27% and the contact phase at 73% over the entire speed range). The duration of overlap decreased from 183 ms at 9 m s^{-1} to 35 ms at 17 m s^{-1} (from 36% to 15% of the total stride duration, P<0.001).

Discussion

To date, limited measurements of the speed dependence of stride-timing variables have been made in galloping animals travelling at a range of speeds over ground. The strains in the limbs of buffalo and elephant have been estimated at one speed from duty factor (Alexander et al., 1979). Treadmill studies are an alternative to field studies; however, treadmill locomotion has limited value as a representation of over-ground locomotion. Gait patterns are altered during treadmill locomotion; for example, stance duration is artificially lengthened (Buchner et al., 1994; Barrey et al., 1993). In addition, the influence of surface could be considerable. The maximum speed that can be attained on a standard equine treadmill without re-gearing (~15 m s^{-1}) is considerably below the top speed of elite equine athletes [the record mean speed for a racehorse over 1/4 mile is 19 m s^{-1} (Russell and McWhirter, 1988)]. Finally, it would be difficult to convince owners or trainers to permit a treadmill study on fit racehorses due to the risk of injury and the disruption to training. This study therefore represents the first detailed investigation of the relationship of footfall timings and limb force to running speed in all four legs of a horse galloping at high speed, under real-world conditions.

The equipment employed during this study was lightweight and non-invasive and did not hinder movement of either horse or rider. The mass of the leg-mounted sensors was similar to the protective boots worn during routine exercise. This means that the horses were able to perform a full training session including maximal speed gallop under effectively normal training conditions. The actual testing session was kept as short as possible in order to ensure genuine high speed data without risking fatigue effects, for instance a drop in stride frequency, which would alter the results (Colborne et al., 2001).

The markedly higher peak vertical force on the forelimbs compared to the hindlimbs, which has been reported at lower speed (Merkens et al., 1993), is indirectly confirmed here at high speed. The hindlimbs have a longer stance duration but are a similar length and therefore sweep through a larger angle during the stance phase. This results in the larger duty factor and therefore a lower predicted force. This may be an adaptation to the major propulsive function of the hindlimbs,

and suggests that the limb should be less stiff (Farley et al., 1993).

The forces predicted in our study are considerably higher than those measured elsewhere. A force of approximately 9000 N was determined using an instrumented horseshoe, which equates to 16.4 N kg^{-1} body weight (Cheney et al., 1973). The peak forelimb force predicted by our study is 24.7 N kg^{-1} body weight, 51% higher. The difference may be explained by the higher speed used here, the presence of a rider and perhaps whether previous measurements were made on the lead or non-lead limb. The mechanical roles of the lead and non-lead limbs during high-speed asymmetrical gaits have not been fully defined. Certainly, the forces experienced by lead and non-lead limbs are markedly different at low speed. A 25% difference has been measured at slow ridden canter and a similar difference has been predicted at 12 m s^{-1} during treadmill locomotion (McGuigan and Wilson, 2003; Merkens et al., 1993). However, it has also been shown during treadmill locomotion that as speed increases, the peak lead and non-lead limb forces converge (Witte et al., 2004), suggesting that the predictions of mean force presented here will become more accurate as speed increases. If the forces do not converge to symmetry as anticipated the presented forces will represent an underestimate for the non-lead limb and an overestimate for the lead limb, showing that previous predictions of maximum limb load during galloping are indeed somewhat low.

Despite the increase in the stance length of the stride and hence the angle through which the limb is swept with increasing speed, the protraction duration fell. This could represent an active contribution to protraction, but given the largely passive nature of the protraction process in the horse (Wilson et al., 2003) this is more likely to result, at least in the front legs, from the muscle–tendon unit of biceps brachii being stretched further at the end of stance (due to higher limb force and greater sweep of leg) storing more energy, and resulting in greater protraction-phase limb acceleration.

The duration of the aerial phase of the stride was independent of speed. When horses increased speed they reduced the overlap between legs, resulting in the limbs functioning more sequentially, rather than synchronously (Fig. 1). Reducing the overlap duration enables horses to achieve speed increases, and accommodate the concomitant decreases in individual limb stance durations, without increasing the aerial phase duration. This is advantageous since a longer aerial phase requires a greater vertical oscillation of the trunk and greater fluctuations in potential energy, which may be energetically expensive. Extrapolating the overlap–speed relationship upwards would predict that overlap would reach zero at a speed of about 20 m s^{-1}. Duration of limb overlap has been suggested as a limit to maximum gallop speed and an indicator of injury risk (Pratt and O'Conner, 1978), though the mechanism is not clear.

The experiment was undertaken on a typical horse-racing surface. The surface over which an individual locomotes acts in series with the leg and the stiffness of the surface would therefore be expected to have an effect on the data collected (McGuigan and Wilson, 2003). The limited data of McGuigan

and Wilson show that a soft surface skews the GRF curve to the right, delaying the time of peak force. However, there was little change in the curve 'fatness' that would affect the force prediction. Although the track used was designed and maintained to achieve constant racing conditions under all weather conditions, jockeys have reported local variations in track stiffness. This may account for some of the variation in the data collected.

This study employs GRF predictions from previous studies carried out during ridden and non-ridden locomotion over force plates and on treadmills with higher surface stiffness than those on which this study was undertaken, and these represent a potential source of error. It has previously been shown that a softer surface, such as Polytrack, acts as a plastic element in series with the limb springs, reducing leg spring stiffness and hence rate of force rise (Ferris and Farley, 1997; Wilson et al., 2001). However, the unloading curve is less affected due to lack of return from the plastic rather than elastic deformation of equestrian surfaces (Zebarth and Sheard, 1985). In addition, vertical impulse must remain constant irrespective of surface properties unless stride frequency changes. Therefore, it seems unlikely that differences in surface properties will substantially affect the results presented here, unless the shape of the GRF–time curve is dramatically altered.

Overall the error of GRF peak force relative to the peak predicted by a sine wave of the same base and area has been shown to be 7% at trot and 3% and 5% for the lead and non-lead limbs at canter, respectively (Witte et al., 2004). An additional error would result from the possibility that the impulse generated by the lead and non-lead legs was different. These errors were 19 and 16%, respectively (Witte et al., 2004) at low speed canter, but this error declined with speed and is likely to be small at the speeds considered here.

The potential influence of a rider on our data, when compared to the un-ridden state used in some of the studies on which our predictions are based, would be to alter the front:hind ratio of forces. However, this appears unlikely due to the jockey's position directly over the centre of mass. Indeed, the data of Merkens et al. indicate that a rider has little or no effect on vertical limb force distribution at canter (Merkens et al., 1991; Merkens et al., 1993).

The techniques employed during this study offer the potential to study large cursorial animals travelling at high speed under field conditions. Studies of the influence of surface and incline on high-speed locomotion can be easily performed. The high peak forces predicted here suggest that previous estimates of the load on the musculoskeletal elements may have been underestimates. Therefore these tools may present the means by which the most appropriate methods of training racehorses can be investigated. The musculoskeletal structures of young racehorses respond to their mechanical environment. Appropriate training regimes that generate realistic stimuli to these structures will reduce the incidence of injury in these animals.

Significantly lower duty factors were measured for the forelimbs compared to the hindlimbs at all galloping speeds,

which in combination with the front–back weight distribution, resulted in higher predicted forces in the front legs. There were no statistically significant differences between the lead and non-lead limbs in any of the variables examined. As speed increased stance time and duty factor dropped but flight duration remained constant. This was achieved by reducing the period of the stride where more than one leg was on the ground.

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