

THE ENERGETIC AND KINEMATIC CONSEQUENCES OF WEIGHTING THE DISTAL LIMB

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Summary

Reason for performing study: It is well known that adding a load to a horse's back increases its energetic costs of locomotion. However the magnitude of the increase resulting from adding the load to the most distal portion of limb has not been measured.

Objectives: Oxygen consumption will be measured in horses with mass added to the back and added to the hooves. Because such mass distribution will alter inertial parameters of the limbs, kinematic measurements will be made to quantify the magnitude of change in limb movement.

Methods: Steady-state oxygen consumption was measured in 6 horses with a load of 2.4 kg. The load was either carried on the back or equally distributed between the four limbs. Modified bell boots kept the mass at the level of P3. Horses trotted on a treadmill at speeds ranging from 2 to 5 m/s (in 0.5 m/s increments). High-speed (250 Hz) digital images were recorded in a sagittal plane and the positions of retro-reflective markers located on standard positions on the limbs were digitized for kinematic analysis.

Results: Loading of the distal limbs produced a 6.7% increase in metabolic rate—an order of magnitude higher than when the mass was added over the back. Although the stride period was 2% longer in horses with loads on the distal limbs, the time of contact and duty factor were not different. Distal limb loading increased the range of motion in hind limbs, but not forelimbs.

Conclusions: The costs of swinging the limbs in the horse are considerable and the addition of weights to the distal limb can have a profound effect on not only the energetics of locomotion, but also the kinematics—at least in the hind limb.

Potential Relevance: The use of weighted shoes, intended to increase the animation of the gait, will increase the metabolic effort of performance horses a disproportionate amount. The additional mass also increases the joint range of motion and potentially increases the likelihood of injury.

Introduction

Anatomists have long argued that limb design in fast running (cursorial) animals has evolved to increase the economy of locomotion (Hildebrand, 1960) by reducing the cost of swinging the limbs. The observed evolutionary changes include relative elongation and reduction of the number of distal limb elements while the muscles that operate the distal joints remained proximal. These changes led to a reduction in the distance between the muscles and the center of rotation of the limb that would decrease the moment of inertia during swing phase and decrease the energy requirements for moving the limb. Thus, the observed cursorial adaptations make sense if a very significant part of the energy cost of locomotion is devoted to swinging the limbs.

However, C.R. Taylor and colleagues provided evidence that, although the limb construction of cursorial mammals intuitively appears to minimize energy costs, the magnitude is

too small to be observed in measurements of oxygen consumption (Taylor *et al.* 1974; Taylor *et al.* 1980). More recent work directed at providing unifying concepts in linking terrestrial locomotion with energetics indicates that major costs in running are due to the rate of force application during the ground contact and, therefore, not during the swing phase (Kram and Taylor 1990).

Other studies in quadrupeds (Steudel 1990) and bipeds (Marsh *et al.* 2004) suggest otherwise. Limb loading and blood flow experiments point to substantial energetic costs that are related to swinging the limbs. In the equine world, the belief that limb mass has an important role in racing success (if not energetic costs) is underlined by the use of lightweight aluminum racing shoes.

The purpose of the present study was to quantify the magnitude of the metabolic costs associated with moving the limbs when mass is added to the distal limb. We hypothesized that such added mass would increase costs sufficiently to be quantifiable using oxygen consumption measurements.

Addition of mass to the distal limbs of the horse is also used to alter the gait characteristics, primarily in the forelimbs, by giving the horse more action, i.e., producing a higher flight arc (Willemen *et al.* 1994; Balch *et al.* 1996). In the present study kinematic measurements were made on both the fore- and hind limbs. We hypothesized that added mass to the distal limb would increase the range of motion.

Materials and Methods

Animals: All horses had been conditioned for a minimum of 6 months to running on the treadmill and to wear an oxygen consumption mask. Two separate sets of measurements were made. The

initial study involved testing the first hypothesis: metabolism would be elevated with increased distal limb weights when compared to carrying a load on the back. For this portion of the study 6 horses were used (4 Arabians, 2 Hackney) with an average mass of 454 ± 10 (SE) kg and oxygen consumption was measured while horses were trotted (3.5 m/s) and cantered (6.0 m/s). In the second study, performed one year later, 6 horses were also used, consisting of the same 4 Arabians and 2 additional Arabians (average mass 505 ± 30 kg). In this portion of the study, oxygen consumption and kinematics were measured over a range of trotting speeds (2.0 to 5.0 m/s) to more closely examine metabolic costs and also quantify the effects of speed on limb range of motion.

Limb weighting: Lead weights were sewn to each of the commercially available boots. The forelimb boots weighed averaged 716 ± 1.1 g and the hind boots averaged 709 ± 8.1 g. After the boot was positioned and fastened on the foot, it was held in place by duct tape wrapped around the boot and hoof surface. This prevented movement of the boot and appended reflective marker either around the hoof (rotational) or up and down (proximal/distal). Once taped in place a cardboard jig was used to reposition the reflective spot in the same location over the coronary band as in the control horses. For each horse, measurements with and without boots were randomized. To determine the cost of carrying the load on the back, the boots were secured to the surcingle (used in all experiments). Addition of weight to the surcingle maintained the normal distribution of weight over the fore- and hind limbs (Wickler, *et al.* 2001). Horses were acclimated to wearing the weighted boots for 30 minutes per day on the treadmill, 5 days per week, for one month prior to any measurements. Hind limbs were unshod, while the forelimbs were shod in standard lightweight shoes (average mass 362 ± 10 g).

Oxygen consumption: All measurements of oxygen consumption were made while animals ran on a motorized treadmill¹ after a warm up consisting of 5 minutes of walking (1.8 m/s) and 5 minutes of trotting (3.5 m/s). Air was pulled past a loose-fitting facemask and an aliquot sampled for fractional oxygen content² as detailed by Wickler *et al.* (Wickler *et al.* 2000, 2002). Flow was continuously monitored using a differential pressure transducer³ and calibrated daily using the one-step nitrogen dilution technique (Fedak, *et al.* 1981). Measurements at each speed were made for a minimum of 3 minutes, a time sufficient to achieve a steady-state metabolic rate at these moderate speeds (Wickler *et al.* 2000). Measurements were randomized for each speed and condition (weight over the back or on the limbs). In the preliminary study (trotting 3.5 m/s, cantering 6.0 m/s) each horse was run at each speed and condition combination three times. Horses were never run more than 4 speed/load combinations on any given day.

Kinematics: Kinematic recordings were made at times different than for oxygen consumption measurements. Reflective markers were placed over palpable regions of the hind and forelimb using the reference points from Leach and Dyson (1998). These sites for the forelimb were: 1) scapular spine (20 cm from proximal border of scapula); 2) center of rotation of the shoulder; 3) center of rotation of elbow; 4) center of rotation of carpus; 5) center of rotation of fore fetlock (metacarpophalangeal) joint; and 6) center of rotation of the fore coffin. The hoof was marked with two markers: one anterior and one posterior to assess contact and heel lift. The sites for the hind limb were (Dutto *et al.* 2004): 1) hip/great trochanter; 2) center of rotation of stifle joint; 3) center of rotation of tarsal joint; 4) center of rotation of hind fetlock (metatarsophalangeal) joint; and 5) center of rotation of the hind coffin. The hind hoof was marked similarly to the fore hoof. A digital camera⁴, placed orthogonally, 8 m from the plane of motion recorded at 250 Hz. A calibration grid consisting of 64 markers was filmed each time the camera was set up, for

corrections of camera/lens aberrations. Horses were brought up to speed and held for 45 seconds and then 15 seconds of video were recorded. For each speed and condition, 5 strides were digitized⁵. Kinematic data were used for determination of stride parameters: stride period, time of contact, and duty factor (fraction of stride the foot is in contact with the ground). Data were transformed using direct linear transformation algorithms for two-dimensional data and then filtered using a 4th order Butterworth filter. Swing phase data were time-normalized to the swing phase duration. Proximal markers (scapula, shoulder, elbow, hip and stifle) were corrected for skin displacement (van Weeren *et al.* 1992). Joint angles were measured on the anatomical flexor aspect, which was the caudal/palmar side for all joints except the elbow, hip and tarsus. For each stride/speed/condition, maximal flexion and maximal extension were quantified for the swing phase. The flexion and extension angles reported in table 1 are angles measured from the beginning of swing phase. Range of motion was calculated as the sum of absolute values of maximal flexion and maximal extension during this phase.

Statistical Analysis: For the first study (speeds 3.5 and 6.0 m/s), oxygen consumption measurements were analyzed using a paired t-test⁶ for the trotting and cantering data separately. Also, the fractional change in oxygen consumption for each gait was calculated and these data were subjected to a paired t-test analysis. For the second study (trotting from 2.0 – 5.0 m/s), metabolism data were analyzed using a repeated measures ANOVA⁷ with two within factors testing for effect of speed and condition (back or limb loading). Where a significant speed effect was observed orthogonal polynomial contrasts were applied to determine if there were significant linear or quadratic contrast to the plotted data for all horses. Also, curves (2nd order polynomial) were fitted⁸ to the data for each horse. For kinematic measurements, results for all 5 strides were averaged, and then a repeated measures ANOVA with two within factors was used

to test for effect of speed and condition. A $p < 0.05$ was considered significant. All data are summarized as a mean \pm SE .

Results

Metabolic rates: In the first study, distal limb loading increased metabolism from 1.64 ± 0.05 to 1.75 ± 0.06 mls O_2 g^{-1} hr^{-1} ($p = 0.0083$) at 3.5 m/s and 2.98 ± 0.14 to 3.25 ± 0.17 ($p = 0.0017$) at 6.0 m/s. The fractional increase (0.068 ± 0.016 versus 0.092 ± 0.013 for the trot and canter, respectively) was not significantly different between gaits ($p = 0.0933$). In the second study, metabolism during trotting increased with speed ($p = 0.0001$) and limb loading ($p = 0.0027$) however the interaction between these factors was not significant ($p = 0.5316$). The increased metabolic cost across all speeds ($n = 42$) from 1.504 ± 0.067 to 1.614 ± 0.069 mls O_2 g^{-1} hr^{-1} represents a fractional increase of 0.073. The speed factor had significant linear ($p = 0.0001$) and quadratic ($p = 0.0303$) contrasts, which suggest that the metabolic response to speed would be best fit by a 2nd order polynomial.

[Figure 1 here]

Kinematics: Stride period decreased with speed (Figure 2; $p = 0.0001$) and was 2% longer for horses with weighted boots (boots, filled circles, solid line; control, open circles, dashed line; $P = 0.001$). Time of contact, although it too decreased with speed ($p = 0.0001$), was not different with condition ($p = 0.6617$). Duty factor, the portion of the stride that the foot is in contact with the ground, was not different with condition ($p = 0.0894$) and decreased ($p = 0.0001$) from an average 52.5% of the stride at 2.0 m/s to 32.9% at 5.0 m/s.

[Figure 2 here]

Range of motion during swing phase in the forelimb: Summary results for each joint across all speeds for maximum flexion, maximum extension, and total range of motion (sum of absolute values for flexion and extension) are presented in Table 1. Range of motion increased ($p = 0.0001$) with increasing speed (2.0 to 5.0 m/s) 67% for the shoulder, 68% for the elbow, 25% for the carpus, and 44% for the fore fetlock joint. The angular displacement of the fore coffin joint did not change with speed ($p = 0.522$). The addition of boots did not affect the range of motion for any joint with the exception of the flexion phase of the fore coffin ($p = 0.0125$) and extension phase of the carpus ($p = 0.0159$). In the fore coffin, it resulted in a 25% increase; however, the overall effect on total range of motion was not different ($p = 0.128$). The carpus joint exhibited a five percent increase in its range of motion over the range of speeds during extension. No significant interaction between distal limb loading and speed was observed in the forelimb.

Range of motion during the swing phase in the hind limb: Summary results for each joint across all speeds for maximum flexion, maximum extension, and total range of motion (sum of the absolute values for flexion and extension) are also presented in Table 1. Range of motion changed ($p = 0.0001$) with increasing speed (2.0 to 5.0 m/s) for all joints. In the hip, range of motion decreased 31% while range of motion increased in the stifle (35%), the tarsus (43%), the hind fetlock joint (12%) and the hind coffin (25%). The addition of boots did not affect the range of motion of the hip ($p = 0.104$), but increased the range of motion of the stifle (22%, $p = 0.0003$), tarsus (9%, $p = 0.0063$), and hind fetlock joint (11%, $p = 0.0044$). The total range of motion in tarsus joint exhibited a significant ($p = 0.0297$) interaction between distal limb loading

and speed where the rate of increase was greater with distal limb loading. Boots decreased the range of motion in the distal coffin joint (22%, $p = 0.0049$).

Discussion

Loading of the distal limbs produced an increased metabolic rate of an order of magnitude more than predicted from back loading. Addition of this additional weight to the back of our horses would be expected to increase metabolism by less than 0.6% (Wickler *et al.* 2001) which is below the limits of detection using our oxygen consumption system. These findings provide a cogent demonstration of the importance of reducing limb mass as a strategy for reducing metabolic costs of locomotion in horses.

The role of reducing limb mass in reducing the cost of locomotion has not always been supported by the data. In earlier work, Taylor *et al.* (1974) compared the metabolic costs of running in gazelles, goats and cheetahs, of similar mass, and approximately the same limb lengths, but with substantially different limb anatomy. The gazelle provided the example of an animal that had an elongated distal limb and a concentration of muscle (and hence mass) more proximally, close to the pivot point of the limb rotation. In contrast, the cheetah provided the example with heavy distal limbs. Despite the differences in anatomy, the costs of locomotion were not different. In another study, Taylor *et al.* (1980) added masses (equivalent to 20 and 30% of body mass) to the back of rats, dogs, humans and ponies. The increase in metabolic costs were in equal proportion to the amount of weight added, i.e. if a weight equal to 20% body weight were added, metabolic rate increased 20%. They concluded that there was not detectable cost of swinging the limbs because, if limb mass made an important contribution to the costs of locomotion, then, a 20% load on the back should increase the costs less than 20%.

More recent work providing a unifying concept in the energetics of running also implicitly assumes there is no cost to swinging the limbs. Kram and Taylor (1990) demonstrated that the cost of locomotion was inversely proportional to the time of contact (duration of stance phase). Specifically, the more rapidly force needed to be produced (the shorter the time of contact), the higher costs. Because the costs were determined by time of contact, with no contribution by swing time, the role of limb mass in contributing to energetics costs were, apparently, insignificant. The present data do not support that conclusion; Addition of distal mass resulted in no change in time of contact, but did increase metabolic rate.

Additionally, there are a number of studies indicating that limb mass does have an effect on energetic costs. Loads added to the lower extremities in humans' increased aerobic demands (Claremont and Hall, 1988; Martin, 1985; Myers and Steudel, 1985). It was not obvious that these results could be applied to quadrupeds so Steudel (1990) then applied 770 grams either to the back or equally distributed on the metatarsals and radius/ulna of dogs weighing an average of 22.5 kg. Limb loading increased metabolic rate 13% above the loading on the back. The results from the current study on horses support the importance of limb mass in determining energetic costs of running.

The partitioning of energy requirements into the swing and stance phase of a stride is difficult because of the complexity of integrating muscle function. Different muscle fiber types have different rates of energy consumption; forces (and hence costs) are altered by the relative proportions of musculature contracting concentrically and eccentrically, and by the action of antagonistic and protagonistic muscles. Although electromyographic activity (Robert *at al.* 2000) can provide some insight on which muscles are active and when that activity occurs, it is unable to provide enough information to estimate energetic costs. One estimation of metabolism has

been made by measuring blood flow in the hind limb musculature of a running biped, the guinea fowl (Marsh *et al.* 2004). They estimated that 26% of the energy for running is consumed by muscles used to swing the limbs, thus accounting for a rather sizeable portion of the cost of locomotion. It seems reasonable, then, that weighting of the limbs would have a significant effect on metabolism.

Another purported effect of increasing mass on the hoof is to alter the kinematics. In the present study, values were similar to those reported in previous studies for stride parameters (Hoyt *et al.* 2002) and for joint angles (Clayton *et al.* 2002; Back 1993) Weight boots produced a small increase (2%) in stride period, similar to that observed in a study of 12 horses with 478 g shoes (at 4.0 m/s) in which stride period was increased 1.7% (Willemen *et al.* 1997). In the present study, there were no changes in time of contact or duty factor over the 5 speeds measured. In some studies, addition of shoes increased animation of the forelimb (higher flight arc of the distal limb and a greater range of motion) in horses trotting on a treadmill at 4.0 m/s (Willemen *et al.* 1997). In a study comparing 6 horses trotting over ground at ~ 3.33 m/s with and without shoes (365 g shoes), flight arc was not statistically different but timing of the peak of the flight arc occurred later in the shod horses (Singleton *et al.* 2004). In the present study, both fore- and hind limb joints were measured and examined over a range of trotting speeds. Contrary to our hypothesis, the expected increases in range of motion were not observed in the forelimb. In humans, addition of mass to the foot does not necessarily produce many changes in temporal or kinematic variables (Martin 1985; Burkett *et al.* 1985). However, the range of motion was exaggerated in the hind limb by addition of distal weights.

The increase in energetics costs and the increase range of motion likely arise because of changes in the inertial parameters of the hoof. A theoretical study suggested that changes in the

mass of the distal mass of the forelimb would have large effects on the kinetics of the proximal limb (Lanovaz and Clayton 2001). In a follow-up study, using three shoeing conditions of the front hoof (unshod, flat shoes and egg bar shoes), additional mass on the hoof required that elbow flexors generate more energy in early swing and the elbow extensors generate more energy in late swing. In the distal limb, energy absorption increased with added mass during early swing (Singleton *et al.* 2004). These changes in inertial parameters are key to linking energetics to the swinging of the limbs. While the percentage increase in metabolism with addition of weight boots was not dependent upon speed (either across the range of trotting speeds or from the trot to the gallop), the absolute increases in metabolism become progressively more pronounced as speed is increased.

The results from this study emphasize the substantial energetic costs associated with alterations in the distal limb mass—an order of magnitude above the costs of placing that on the back of the horse. Changes in the inertial properties of the limbs also alter the kinematics and kinetics of the limbs. In order to control the movement of limbs with greater inertia, more energy must be generated and absorbed to control both flexion and extension throughout swing. Failing that, muscles and tendons may be exposed to excessive stretching leading to injury (Hreljac 1995).

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Manufacturers addresses:

- 1 SATO I, Sato AB, Lovisedalsvagen, Knivsta, Sweden
- 2 Sable Systems, Henderson, NV, USA
- 3 Smart Gauge, Meriam Instruments, Cleveland, OH, USA
- 4 PCI, 250, Redlake Imaging Corp., San Diego, CA, USA
- 5 Peak Motus, Peak Performance Technologies, Inc., Denver, CO, USA
- 6 Statview, Abacus Concepts, Berkeley, CA, USA
- 7 Super Anova, Abacus Concepts, Berkeley, CA, USA
- 8 Microsoft Excel®

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Figure 1:

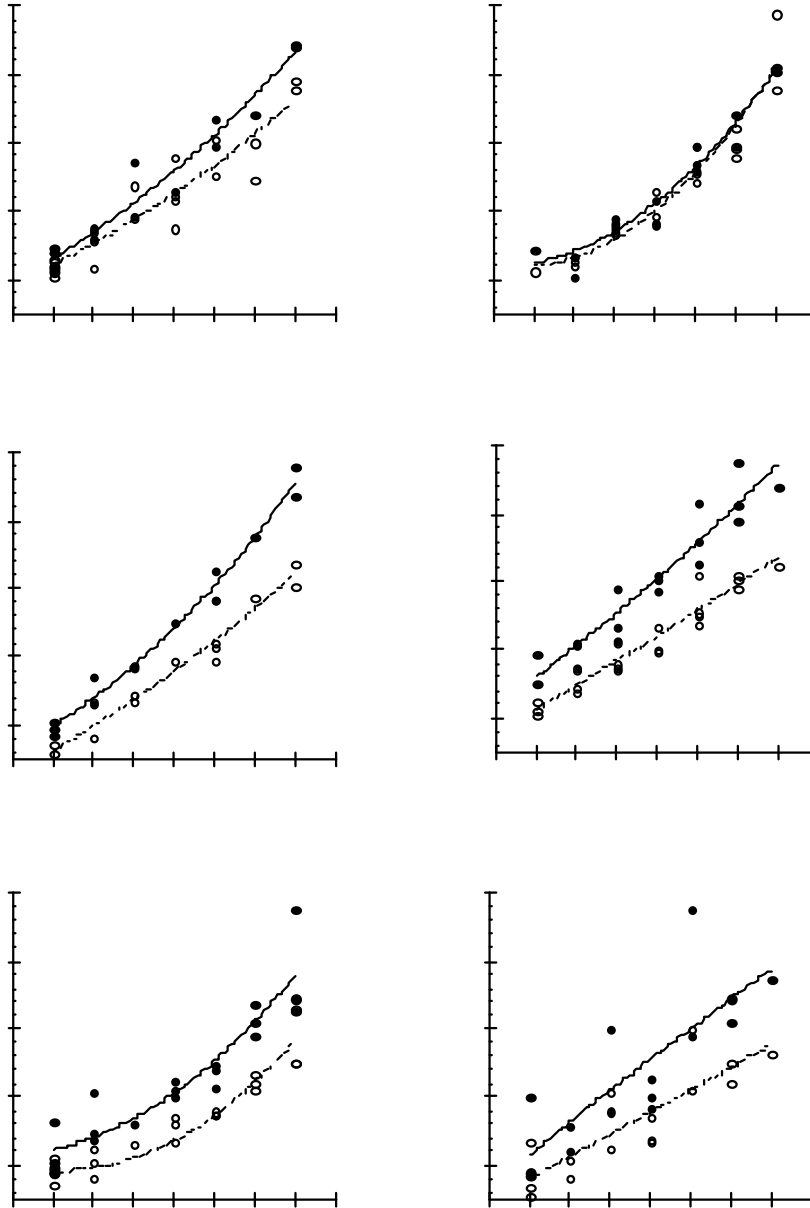


Figure 1: Oxygen consumption (expressed as mls O₂ per gram body mass per hour) as a function of trotting speed for 6 Arabian horses. Addition of mass to the distal limbs (boots, filled circles, solid line) elevated metabolism over addition of the mass to the back (control, open circles, dashed line). The lines represent 2nd order polynomials fit to the data (rationale for using 2nd order polynomials reviewed in Wickler et al. 2000).

Figure 2

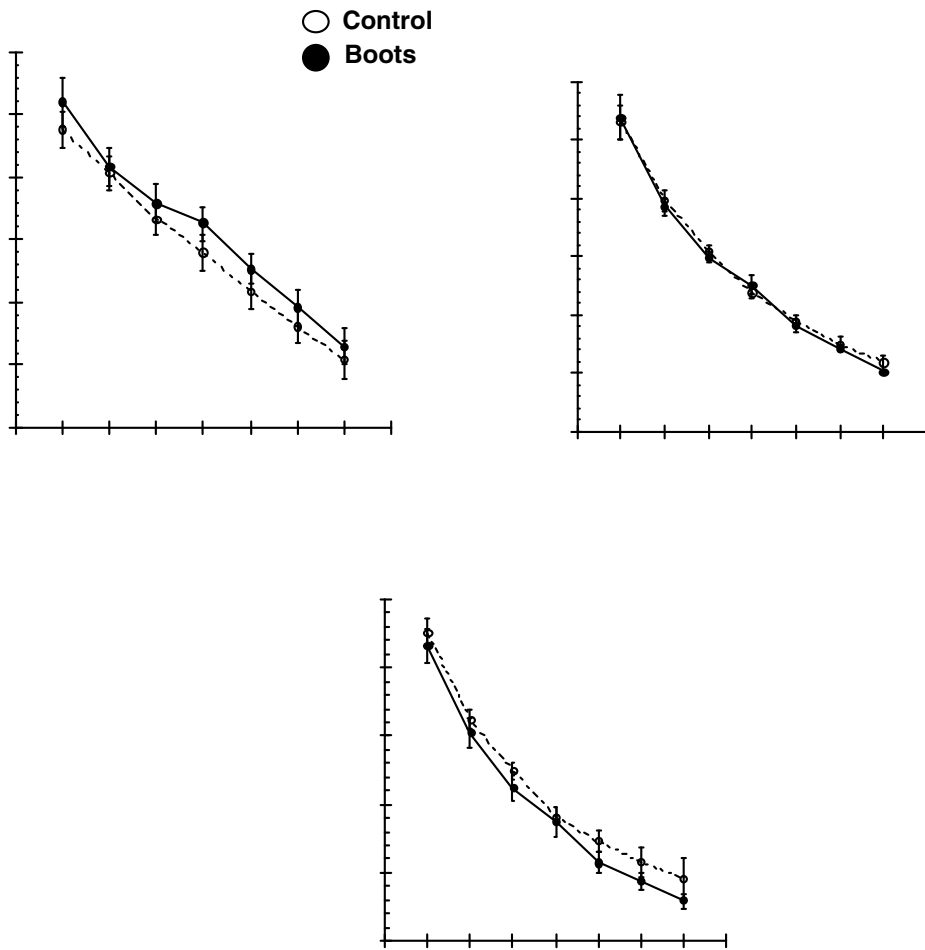


Figure 2: Stride parameters for horses with mass added to their back (control, open circles, dashed line) or to the distal limbs (boots, filled circles, solid line). Stride period, time of foot contact and duty factor (portion of stride in which the foot is in contact with the ground) all decreased with speed. Stride period was longer for horses with mass added to their distal limbs.

Table 1

Fore limb						
Joint	Flexion		Extension		Total	
	control	boot	control	boot	control	boot
Shoulder	-14.2 (0.5)	-14.2 (0.7)	21.1 (0.6)	21.8 (0.7)	35.3 (0.9)	36.0 (1.1)
Elbow	-50.1 (1.2)	-49.4 (1.6)	27.6 (1.7)	30.4 (1.7)	77.7 (2.7)	79.9 (2.9)
Carpus	-69.9 (1.6)	-67.9 (2.6)	73.3 (1.6)	77.2 (1.4)	143.2 (2.9)	145.2 (3.6)
Fore fetlock	-53.5 (2.1)	-48.3 (2.8)	43.4 (1.5)	44.2 (1.8)	96.9 (2.8)	92.5 (3.4)
Distal fore coffin	-41.2 (1.1)	-31.9 (1.2)	12.8 (1.0)	15.7 (1.0)	54.0 (1.9)	47.6 (1.5)
Hind limb						
Joint	Flexion		Extension		Total	
	control	boot	control	boot	control	boot
Hip	-2.9 (0.4)	-3.6 (0.3)	13.8 (0.4)	15.6 (0.5)	16.7 (0.6)	19.2 (0.7)
Stifle	-12.8 (0.8)	-18.6 (0.9)	36.4 (1.0)	41.2 (1.3)	49.2 (1.8)	59.8 (2.1)
Tarsus	-45.7 (1.2)	-50.4 (1.3)	44.8 (1.0)	47.9 (1.3)	90.5 (2.1)	98.3 (2.5)
Hind fetlock	-50.7 (0.9)	-60.2 (1.0)	56.1 (1.0)	58.8 (1.2)	106.8 (1.7)	119.0 (2.0)
Distal hind coffin	-44.3 (1.1)	-35.5 (0.9)	30.6 (1.1)	22.1 (1.0)	74.8 (1.8)	57.6 (1.7)

Table 1. Average range of motions for each joint during swing phase. Values (standard error in parenthesis) are for maximum angles during flexion and extension of the joint as measured from the beginning of the swing phase. The total range of motion was calculated by adding the absolute values for flexion and extension. Shaded values are different between control and boots ($P < 0.05$).