

Redistribution of Ground Reaction Forces in Experimentally Induced Equine Carpal Lameness

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Summary

A computerized force platform was used to measure force redistribution due to lameness. Peak and time integrated vertical and horizontal forces as well as contact time were analyzed in 10 horses pre and post surgical induction of carpal lameness. Analysis of ground reaction forces in the sound horses showed vertical forces and horizontal deceleratory forces to be greater in the forelimbs than the hind limbs. Horizontal acceleratory forces were significantly greater in the hind limbs. The contact time of the forelimbs was significantly greater than that of the hind limbs. After induction of a visible left carpal lameness, there was a relative shift in vertical forces from left to right in both the fore and hind limbs. Horizontal deceleration forces decreased significantly in the left (lame) forelimb and increased in the opposite forelimb while horizontal acceleratory forces decreased in the left hind limb compared to the right. Contact time did not change. These results indicate an alteration in the mechanics of locomotion due to lameness resulting in a relative increase in vertical forces and horizontal deceleration forces by the opposite forelimb.

Index terms: Force plate, locomotion, kinetics.

Introduction

Since the late 1800s, many attempts have been made to characterize equine locomotion (Leach and Dagg, 1983a; Leach and Dagg, 1983b). A recent advance in the field of kinetics has been the use of the force plate to measure the ground reaction forces exerted by the limbs in multiple directions (Cavagna, 1985). Various investigators have quantified different aspects of normal equine locomotion patterns utilizing force plates (Pratt and O'Connor, 1976; Schryver *et al.*, 1978; Steiss *et al.*, 1982; Merklings *et al.*, 1985). Vertical ground reaction forces have also been used for the evaluation of the efficacy of drugs and various treatment regimes in alleviating lameness (Gingerich *et al.*, 1979; Auer *et al.*, 1980; Gingerich *et al.*, 1981; Silver *et al.*, 1983). However, few studies exist quantifying the changes in ground reaction forces during lameness (Cavagna *et al.*, 1983).

Despite the many advances in the study of equine biomechanics, the lameness evaluation remains a purely subjective analysis of gait modifications effected by the lame

horse and an attempt by the diagnostician to correlate these visual alterations with a specific musculoskeletal lesion. Many different methodologies have been employed with the aim of quantitative characterization of lamenesses (Ratzlaff *et al.*, 1982; Fredericson *et al.*, 1980; Ratzlaff and Grant, 1985; Auer and Butler, 1985). Force plate analysis of the lame horse allows a quantification of the degree of lameness. It also enables an evaluation of the changes in ground reaction forces by all four limbs in the attempt by the horse to compensate for a lameness, allowing accurate predictions concerning the anatomic sites most susceptible to secondary injury.

The aim of this study was to quantify the ground reaction forces during the normal equine trot and to document the changes resulting from a standardized carpal lameness. In order that this work may have clinical as well as scientific application, a moderate trotting speed was chosen to approximate speeds commonly employed when evaluating a horse for signs of lameness.

Materials and Methods

Horses. Ten horses used in this analysis were chosen from an independent arthritis study. Nine were Standardbreds and one was a Quarter Horse cross. Weights ranged from 385 to 545 kg. The horses had no visible or palpable musculoskeletal defects and all had normal radiographic appearances of the carpal joints and normal synovial fluid parameters in the intercarpal joints at the outset of the project. All showed a negative response to flexion tests of all joints in fore and hind limbs during lameness examination.

A minimum of a one-week acclimatization period was allowed for the horses during which they were immunized, dewormed and their hooves were trimmed and balanced. During this period, the horses were trained to run on a high speed treadmill and underwent force plate analysis to establish control values.

Experimental induction of carpal lameness. Following the acclimatization and control period, the horses underwent general anesthesia and arthroscopic surgery to create a 1-cm diameter, full-thickness articular cartilage defect on the dorso-lateral aspect of the distal surface of the left radial carpal bone using a motorized abrading device. (Dyonics, Inc., Andover, MA 01810). Photographs were taken to document the appearance of the abrasion site. A one-week postoperative period was allowed during which the horses were stall-rested.

During the subsequent four weeks a program of controlled exercise was used in conjunction with the surgical lesion to induce secondary intercarpal joint disease. Each horse received an average of 20 minutes trotting time per day on a high speed motorized treadmill at speeds ranging from 4 to 7 m/sec. Following completion of this program all of the horses had an easily observable left front limb lameness.

Force plate analysis. Ground reaction forces were measured to evaluate the normal equine trot and to quantify change in weight bearing occurring after induction of lameness. A Kistler model Z4852 (Kistler Instruments, Amherst, NY 14120-5091) piezoelectric quartz crystal force plate was used to measure ground reaction forces in the vertical, horizontal and lateral directions. The horses were led at the trot over the force plate which was located in a rubber surfaced gait path in an indoor arena. Average velocity and changes in velocity during each trial were determined with a series of photodiodes placed along the gait path at regular intervals. The output of the photodiodes was recorded on a storage oscilloscope for analysis. Only recordings where the

average velocity was between 2.7 and 2.9 m/sec, with less than 10% variation in this velocity during the trial, were accepted and stored in a data file on a microcomputer (Data General Desktop 10SP, Data General Corporation, Southboro, MA 01581). Ten trials consisting of runs during which the left fore and left hind hoof hit the plate and ten trials consisting of runs during which the right fore and right hind hoof hit the plate were recorded. This protocol was repeated on each horse after induction of the left carpal lameness. Peak vertical (PF_z) and peak horizontal deceleration and acceleration forces ($PF_{y,d}$ and $PF_{y,a}$), time integrated vertical (IF_z) and time integrated horizontal deceleration and acceleration forces ($IF_{y,d}$ and $IF_{y,a}$) and contact times were quantified from the force traces for each of the horses (Table 1). Forces were normalized to the horse's body weight (1G). To normalize for differences in absolute values between individual horses as well as for the changes in absolute values between the first and second force plate analysis in the same horse, the redistribution of weight bearing was evaluated by comparing ratios of left to right limb parameters for the forelimbs and the hind limbs.

The individual variation between trials for each horse was minimal (Seeherman *et al.*, 1987). Statistical analysis was performed on the left limb to right limb ratios using paired t-test statistics on the mean values from the 10 horses.

Results

Characterization of the equine trot

Vertical forces. The mean peak vertical force (PF_z) exerted by each front limb was 1.12 ± 0.01 G (Table 2). This value was 10.25% higher ($P < 0.05$) than the mean PF_z exerted by each hind leg (Fig. 1a). The time integrated vertical force (IF_z) also differed significantly between front and hind limbs ($P < 0.05$). The mean IF_z of the front limbs was 21.6% higher than that of the hind limbs.

Contact time. The mean contact time (time which the foot spends in contact with the force plate) of the front legs was 242.8 milliseconds (msec). The mean contact time of the hind limbs was 9.2% less than that of the front limbs ($P < 0.05$).

Horizontal deceleration forces. The mean peak horizontal deceleration forces ($PF_{y,d}$) of the forelimbs of the trotting horse was 0.108 ± 0.004 G (Fig. 1b). This value was 31.5% higher ($P < 0.05$) than the mean peak horizontal deceleration force of the hind limbs. The principal peak horizontal deceleration forces of the trotting horse appear therefore to be exerted by the forelimb half of the diagonal pair which contact the

TABLE 1 Index of abbreviations of vertical and horizontal ground reaction forces.

PF_z	Peak vertical force (G)
IF_z	Time integrated vertical force (G · ms)
CT	Contact time (msec)
$PF_{y,d}$	Peak horizontal deceleration force (G)
$IF_{y,d}$	Time integrated horizontal deceleration force (G · msec)
$PF_{y,a}$	Peak horizontal acceleration force (G)
$IF_{y,a}$	Time integrated horizontal acceleration force (G · msec)

TABLE 2. Vertical and horizontal ground reaction forces of normal trotting horses.

PARAMETER	Front Limb MEAN (SE) n = 10	Hind Limb MEAN (SE) n = 10
PF _z (G)	1.12 (0.01)	1.01 (0.06)
IF _z (G · ms)	159.1 (4.2)	124.8 (2.6)
CT (ms)	242.8 (3.2)	220.5 (2.6)
PF _{y,d} (G)	0.108 (0.004)	0.074 (0.005)
IF _{y,d} (G · ms)	8.87 (0.34)	4.83 (0.32)
PF _{y,a} (G)	0.082 (0.003)	0.102 (0.002)
IF _{y,a} (G · ms)	5.09 (0.27)	6.44 (0.27)

Refer to Table 1 for index of abbreviations

There was a statistically significant difference ($P < 0.05$) between the means of the fore and hind limbs for all parameters

ground together. The time integrated horizontal deceleration forces (IF_{y,d}) were 45.6% higher in the forelimbs as compared to the hind limbs ($P < 0.05$).

Horizontal acceleration forces. Mean peak horizontal acceleration forces (PF_{y,a}) were 0.082 ± 0.003 G in the forelimbs and 0.102 ± 0.002 in the hind limbs of the trotting horse. This represents a 24.4% greater peak force ($P < 0.05$) exerted by the hind limbs as compared to the forelimbs during this phase of the stride. Time integrated horizontal acceleration forces (IF_{y,a}) paralleled this difference

Redistribution of Ground Reaction Forces in the Lamé Horse

Vertical forces. Ratios of left-to-right forelimb peak vertical forces were compared prior to and after induction of left forelimb lameness (Table 3, Fig. 2a). There was a significant decrease in the left/right ratio ($P < 0.05$) signifying a decrease in relative weight bearing by the left as compared to the right forelimb. An evaluation of individual limb PF_z data shows the change to be due to a decrease in weight bearing by the left forelimb while the right forelimb did not significantly alter mean PF_z with lameness. The ratios of left to right hindlimbs paralleled this change: There was a relative decrease in the left hind limb peak vertical force as compared to that of the right hind limb ($P < 0.05$) due to a decrease in weight bearing by the left hind limb. Time integrated vertical forces (IF_z) showed similar changes with a relative decrease in the left/right forelimb and hindlimb ($P < 0.05$) ratios.

Contact time. Analysis of the ratio of left forelimb to right forelimb contact time prior to and after induction of left carpal lameness showed no statistically significant changes. Similarly, the hind limb contact time ratios did not change due to left forelimb lameness.

Horizontal deceleration forces. There was a significant decrease ($P < 0.05$) in the ratio of left forelimb peak horizontal deceleration (PF_{y,d}) to right forelimb PF_{y,d} after induction of carpal lameness (Fig. 2b). This is due to a decrease in left forelimb PF_{y,d} as well as an increase in PF_{y,d} exerted by the right forelimb. Analysis of relative changes in PF_{y,d} of the hind limbs shows no significant alterations due to lameness. Time integrated horizontal deceleration forces (IF_{y,d}) showed similar changes. The left forelimb

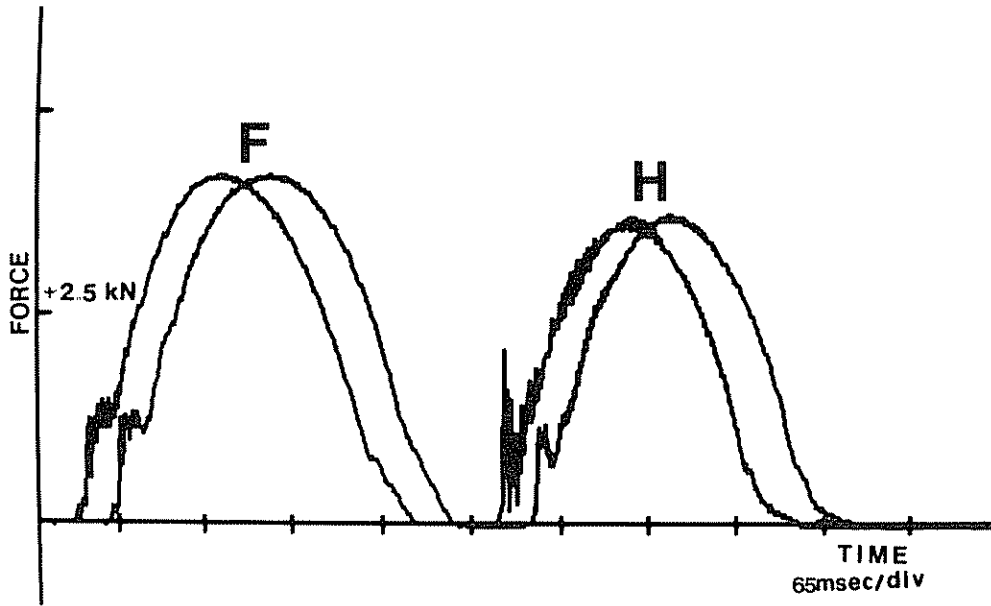


FIGURE 1a. Peak vertical forces (PF_z) of the left and right forelimbs (F) and hind limbs (H) in a sound horse. Left fore and left hind traces are offset to the right.

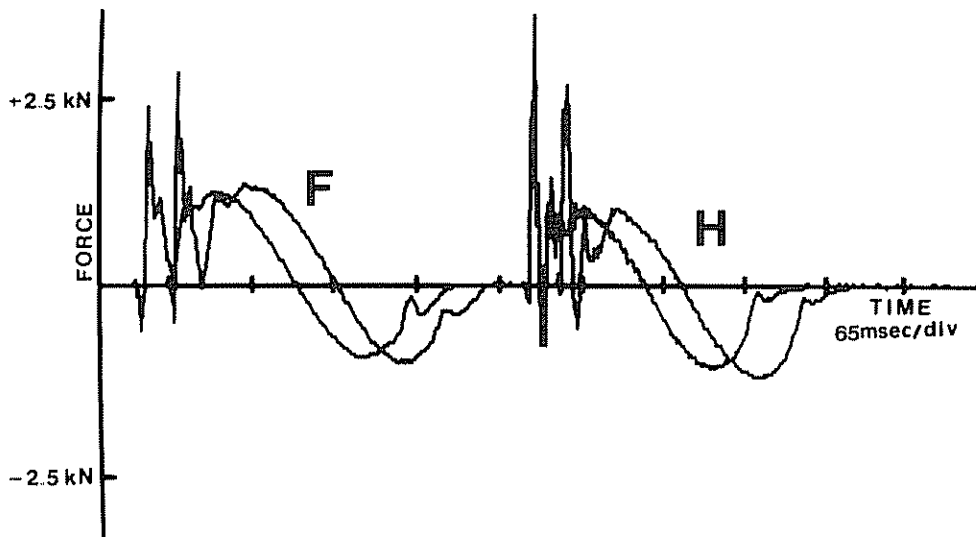


FIGURE 1b. Peak horizontal forces (PF_y) of the left and right forelimbs (F) and hind limbs (H) of a sound horse. Left fore and left hind traces are offset to the right. Horizontal deceleration forces are positive and horizontal acceleration forces are negative.

TABLE 3. Vertical and horizontal ground reaction forces in trotting horses pre and post induction of left carpal lameness

PARAMETER		FORELIMB		HIND LIMB	
		Pre	Post	Pre	Post
		MEAN (SE) n = 10	MEAN (SE) n = 10	MEAN (SE) n = 10	MEAN (SE) n = 10
PF _v (G)	left	1.13 (0.02)	1.00 (0.28)*	1.02 (0.02)	0.94 (0.02)*
	right	1.12 (0.12)	1.11 (0.02)	1.00 (0.02)	0.98 (0.013)
	L/R ratio	101.56 (0.86)	89.6 (2.70)†	102.01 (2.10)	95.34 (1.92)†
IF _v (G · msec)	left	163.2 (3.6)	149.5 (5.1)*	124.6 (3.7)	118.1 (2.4)*
	right	155.1 (7.5)	162.8 (3.2)	124.9 (3.8)	126.9 (2.9)
	L/R ratio	101.99 (1.5)	91.8 (2.49)†	100.2 (2.4)	93.9 (2.0)†
CT (ms)	left	244.7 (4.5)	251.5 (3.2)	219.6 (3.9)	227.1 (4.8)*
	right	240.9 (4.6)	246.4 (4.1)	221.5 (3.6)	225.2 (4.3)
	L/R ratio	101.7 (1.1)	101.3 (1.1)	99.6 (1.2)	100.9 (1.2)
PF _{y,d} (G)	left	0.115 (0.004)	0.095 (0.006)*	0.078 (0.008)	0.082 (0.005)
	right	0.100 (0.006)	0.111 (0.006)*	0.070 (0.008)	0.07 (0.007)
	L/R ratio	115.14 (7.57)	87.11 (7.52)†	119.55 (16.67)	23.70 (12.47)
IF _{y,d} (G · msec)	left	9.38 (0.34)	7.96 (0.37)*	5.12 (0.34)	5.71 (0.29)
	right	8.36 (0.56)	9.74 (0.50)*	4.55 (0.53)	4.68 (0.46)
	L/R ratio	117.43 (9.56)	84.56 (5.40)†	120.95 (13.24)	136.00 (18.93)
PF _{y,a} (G)	left	0.079 (0.006)	0.078 (0.006)	0.098 (0.004)	0.086 (0.003)*
	right	0.085 (0.003)	0.076 (0.005)*	0.105 (0.003)	0.111 (0.005)
	L/R ratio	95.38 (7.36)	102.27 (6.73)	93.44 (3.53)	80.77 (6.12)†
IF _{y,a} (G · msec)	left	4.91 (0.47)	5.12 (0.48)	6.15 (0.33)	5.11 (0.40)*
	right	5.27 (0.27)	4.72 (0.41)*	6.72 (0.41)	7.35 (0.43)
	L/R ratio	94.13 (8.05)	80.77 (6.12)†	92.21 (2.88)	73.41 (8.33)†

Refer to Table 1 for index of abbreviations.

*Denotes significant difference ($P < 0.05$) between the means of the ground reaction forces pre and post induction of left carpal lameness.

†Denotes significant difference ($P < 0.05$) between the ratios of the mean forces for the left limb/right limb pre and post induction of left carpal lameness.

IF_{y,d} decreased relative to the right forelimb ($P < 0.05$) while there was no significant difference in the hind limb ratios. These results demonstrate a significant shifting of the horizontal deceleration forces in the lame horse away from the lame forelimb with a comparable increase by the contralateral forelimb.

Horizontal acceleration forces. A comparison of left to right peak horizontal acceleration forces (PF_{y,a}) of the forelimbs showed no significant changes prior to and after carpal lameness. The left/right hind limb PF_{y,a} ratios did demonstrate significant changes ($P < 0.05$). There was a decrease in the ratio after lameness signifying a relative decrease in left hind PF_{y,a} as compared to right hind PF_{y,a}. This change is due to a decrease in mean PF_{y,a} in the left hind limb of the horses without a change in the right hind limb force. Time integrated horizontal acceleration forces (IF_{y,a}) demonstrated a significant increase in the ratio of left/right forelimb IF_{y,a} ($P < 0.05$) and a decrease in this ratio in the hind limbs ($P < 0.05$) due to left forelimb lameness. These results signify a decreased relative contribution to the horizontal acceleration phase of the equine trot

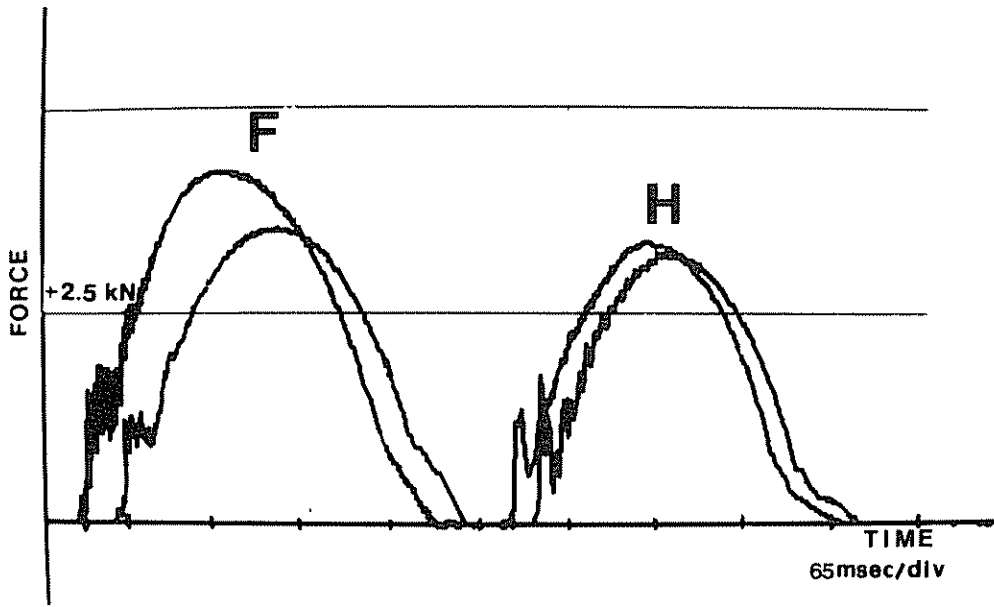


FIGURE 2a Peak vertical forces (PF_z) of the left and right forelimbs (F) and hind limbs (H) of a horse with experimentally induced left carpal lameness. Left fore and left hind traces are offset to the right. Note the relative decrease in Left PF_z /Right PF_z in both fore and hind limbs.

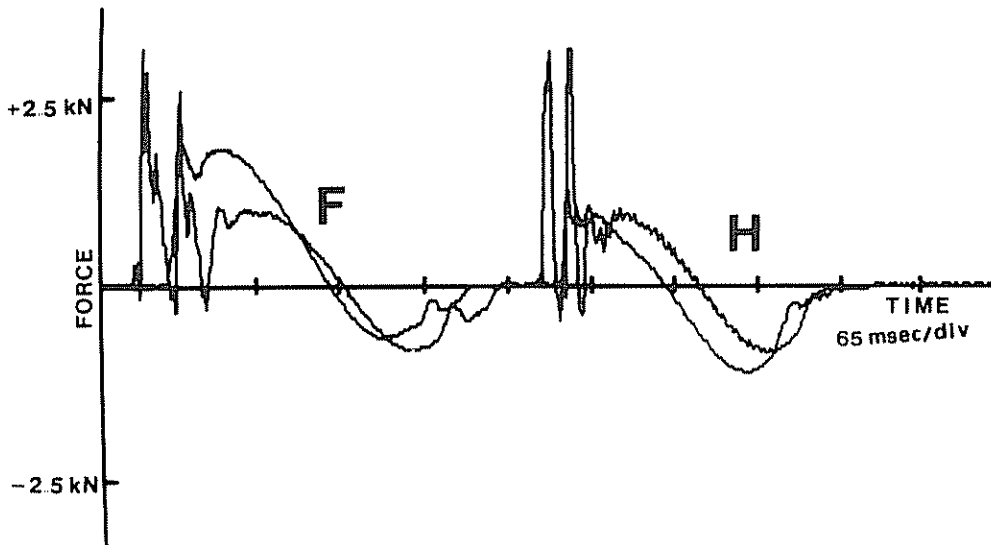


FIGURE 2b Peak horizontal forces (PF_y) of the left and right forelimbs (F) and hind limbs (H) of a horse with experimentally induced left carpal lameness. Left fore and left hind limb traces are offset to the right. Horizontal deceleration forces are positive and horizontal acceleration forces are negative. Note the relative decrease in left PF_y /right PF_y in the forelimbs.

by the concurrently weight bearing right forelimb-left hind limb pair as compared to the opposite pair (left forelimb-right hind limb) due to left carpal lameness.

Discussion

The results of this study quantify ground reaction forces during the equine trotting gait and illustrate the changes in these forces due to a standardized carpal lameness. An attempt has been made to allow maximum application of the results of this study to the clinical lameness evaluation of a horse suffering from carpal lameness. The speeds at which all analyses were performed correlates with the speed at which the majority of lameness examinations take place. The lesion causing the lameness, although experimentally induced, closely parallels full thickness cartilage lesions seen commonly in the carpus of the performance horse resulting in acute synovitis and subsequent osteoarthritic changes. Visually the lameness induced by the lesion can be characterized as a mild to moderate left forelimb lameness.

In the sound horse trotting over the force plate at speeds of 2.7–2.9 m/s, the mean peak vertical force of each forelimb was 1.12 G. This was 10.25% higher than the mean peak vertical force exerted by each hind limb. The time integrated vertical force in the sound trotting horse was significantly greater in the forelimbs compared to the hind limbs. Although the trot is a symmetrical two-beat gait with diagonal fore and hind limbs on the ground at approximately the same time, the mean contact time of the forelimbs was 9.2% longer than that of the hind limbs. This dissociation of the diagonal limbs has been previously reported by kinematic studies (Drevemo *et al.*, 1980; Drevemo *et al.* 1980), Patterns of horizontal forces in the sound horse demonstrated a 31.5% greater mean horizontal deceleration force by the forelimbs as compared to the hind limbs. In contrast, peak horizontal acceleration forces were 24.4% higher in the hind limbs than the forelimbs. The order of magnitude of these peak horizontal forces approximated 10% of the peak vertical forces.

These results are explained by the location of the center of mass in the horse which is situated closer to the front limbs of the animal. For this reason the peak vertical forces are higher when the forelimbs strike the ground. This anterior location of the center of mass also explains the differences in horizontal forces. The mechanical work of horizontal locomotion must take place through the center of mass in order to reduce the tendency of rotation of the center of mass. In order for horizontal deceleration to be effected through the center of mass the forces must occur cranial to it and the reverse holds true for horizontal acceleration. For these reasons, the horizontal deceleration forces are greater in the forelimbs and the horizontal acceleration forces are greater in the hind limbs of the horse.

Significant alterations in force patterns due to carpal lameness were observed in the horses in this study. There appears to be a tendency toward overall reduction in vertical forces by the lame horse. Therefore, the analysis of the relative shift in weight bearing was performed by an evaluation of the ratios of left forelimb mean ground reaction forces to right forelimb mean forces and the ratio of left hind limb to right hind limb mean forces. This allowed both a normalization for differences in absolute values between individual horses due to different gait characteristics and also normalized changes in absolute values from the control to the second, post-surgical force plate analysis in the same horse.

There was a significant reduction in the left/right ratio for peak vertical force in both fore and hind limbs due to carpal lameness. This demonstrates a shift in weight bearing away from the lame forelimb and a relative decrease in weight bearing by the ipsilateral hind limb because individual limb PF_z values for the left fore and hind limbs decreased significantly, while the values for the right fore and hind limbs did not change. There was also a reduction of time integrated vertical forces in the left forelimb and left hind limb as compared to the right fore and hind limbs while the contact times did not alter significantly due to the lameness.

Since the reduction in time integrated forces cannot be explained by a decrease in trotting velocity, an alternate explanation may be a change in the mechanics of locomotion due to the lameness. During a complete stride cycle at a constant running speed the average vertical forces exerted by all four limbs (the time integrated force for all 4 limbs divided by the duration of the complete stride) must equal 1G. If the average vertical forces are less than 1G, the center of mass will have a net downward displacement at the end of each stride. The opposite is true for an increase in average vertical force. The only compensation that can occur with a decrease in time integrated force at a constant running speed such as was observed in the lame horses is a reduction in the duration of the total stride due to an increase in stride frequency and a decrease in stride length. At all trotting speeds except the very slowest there is a contact phase and an aerial phase in each stride (Cavagna *et al.*, 1977). Because the contact time remained constant in the lame horses, the reduction in stride duration must occur because of a shortening of the aerial phase of the stride.

This explanation also applies to the overall reduction in peak vertical forces at the same trotting speed in the lame versus the sound horses. A decrease in the aerial phase of the stride will result in a smaller vertical displacement of the center of mass and therefore a decrease in peak vertical force. Although verification of this analysis requires high speed cinematography or a force platform to enable evaluation of a complete stride, it appears that a lame horse may modify patterns of locomotion by adopting a less bouncy gait resulting in a reduction in peak vertical forces.

A marked redistribution of horizontal forces by the lame horse is also evident. A decrease in mean left forelimb $PF_{y,d}$ and a concomitant increase in the right forelimb resulted in a significant reduction in the left/right forelimb peak horizontal deceleration force ratio. The horizontal deceleration force pattern of the hind limbs appeared unaffected by the carpal lameness. There was a smaller but still significant alteration in the horizontal acceleration forces in the lame horses due primarily to a decrease in mean $PF_{y,a}$ by both the right forelimb and left hind limb.

An explanation of these changes in horizontal force patterns may be due to the inability of the horse to decelerate on the lame left forelimb. The compensation for this inability to slow forward motion cannot be performed by the right hindlimb due to the position of this limb behind the center of mass. During the next segment of the stride, compensation can occur and the right forelimb greatly increases the peak horizontal deceleration forces resulting in a maintenance of trotting speed.

The potential of secondary injury resulting from attempts by an animal to compensate for a lameness by altering gait patterns is a significant and widely recognized problem. Through a detailed analysis of changes in ground reaction forces due to lameness, primary areas of concern may be pinpointed. In this study of carpal lameness, it appears that relative vertical loads are increased in the opposite forelimb. The opposite forelimb

also experiences increases in time integrated and peak horizontal deceleration forces potentially increasing risk of injury to this limb.

The characterization of normal gaits as well as abnormal variations is of interest from a clinical as well as a scientific standpoint. An evaluation of the changes in force patterns by a horse with a specific lameness may aid in an anatomical diagnosis of the problem. The "art" of lameness diagnosis stems from the ability of the diagnostician to correlate a characteristic gait pattern with a specific lameness. Eventually it may be determined that these gait patterns have characteristic ground reaction force patterns as seen by force plate analysis. Force plate analysis of normal and pathologic gaits in the horse also allows a quantification of the redistribution of forces among the limbs of a lame horse thus ending speculation concerning the most probable sites of secondary lameness which at this time remains purely theoretical.

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Individual Variation in the Quarter Horse Gallop

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Summary

The individual transverse gallop stride characteristics of four Quarter Horse fillies were documented by means of high-speed cinematography. Horses were approximately thirty months of age and raised and trained similarly. Horses were filmed by two cameras simultaneously (243 frames/sec) while galloping under the standardized conditions of a specially constructed 1.5 m-wide track. Horses were all ridden by one person, using the same saddle and bridle. Limb contact variables determined for 62 strides included stride length and frequency, step lengths, and contact and non-contact durations for single limbs and combinations of limbs. In data analysis, velocity, day and lead effects were partitioned to enable the determination of persistent, individualized gallop stride patterns. Horses differed in average velocity and stride frequency but were not significantly different in stride length or the distance between any two successive hoof impacts. Subjects were found to differ in the duration of contact of the hind lead, fore trail and fore lead limbs; and the non-contact duration of the fore trail and fore lead limb. In the gallop stride cycle, horses differed in fore trail diagonal bipedal contact, fore trail unipedal contact and fore bipedal contact. Individual idiosyncracies of the gallop stride therefore appeared primarily in fore limb timing patterns. Methods utilized in this study may be useful for objective biomechanical gait evaluations of individual horses.

Index terms: Biomechanics; kinematics; gait; locomotion.

Introduction

Individual characteristics of motion are considered major contributors to successful competitive performance of equine athletes. Horses are currently selected for breeding and purchase primarily on the basis of subjective measures such as traditional conformation judging, visual appraisal of movement patterns and pedigree evaluation. High speed cinematography may be used in the future to augment these processes by providing objective measures of an individual horse's gait patterns (Leach and Crawford, 1983).

Motion patterns of the galloping horse were first objectively documented by Muy-