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Locomotor Forces of Galloping Horses

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Summary

Vertical forces exerted by galloping horses were measured using instrumented shoes nailed to each hoof. Each shoe consisted of an aluminum racing plate, aluminum transducer mount, and piezoelectric force transducer. The transducers were positioned over the center of the frog of each foot. Simultaneous recordings of the vertical forces exerted by all four feet were obtained from consecutive strides of each horse as it galloped through the straightaways and turns of a one-half mile (0.8 km) research track. The temporal patterns and force-time curves of each limb were repetitive for successive strides. On the straightaways, the greatest forces were exerted by the lead forelimb followed by the lead rear, non-lead fore, and non-lead rear limbs. The mean peak forces and ranges, expressed as a percentage of the total force exerted on the transducers from the four feet, were 29.3 (24.6–33.4), 26.4 (16.2–32.4), 23.3 (18.4–30.4), and 21.0 (17.0–29.3) for the lead front, lead rear, non-lead front, and non-lead rear limbs, respectively. On the turns the greatest forces were exerted by the lead forelimb followed by the non-lead fore, lead rear, and non-lead rear limbs. The mean peak forces and ranges, expressed as a percentage of the total vertical force, were 30.1 (26.3–35.1), 26.3 (23.8–31.5), 23.0 (17.2–25.3), and 20.7 (17.6–25.0) for the lead fore, non-lead fore, lead rear, and non-lead rear limbs, respectively. The greater vertical forces exerted by the front legs of horses galloping through the turns may help explain the propensity for forelimb injuries in racing Thoroughbred horses.

Index terms: Biokinetics; locomotion.

Introduction

Force plates have been used to measure the ground reaction forces exerted by horses moving at various gaits (Goodship *et al.*, 1983; Pratt and O'Connor, 1976; Quddus *et al.*, 1978; Kingsbury *et al.*, 1978; Schryver *et al.*, 1978; Steiss *et al.*, 1982) and under a variety of conditions (Auer *et al.*, 1980; Cheney *et al.*, 1973; Ratzlaff *et al.*, 1985a). The primary advantages of using a force plate to measure locomotor forces are the ease of operation and ability to measure the horizontal force components as well as the vertical component. The disadvantages of the force plate include the inability to measure forces exerted in repetitive strides, difficulty in recording forces exerted by horses moving at the faster gaits, and problems in overcoming the animal's avoidance of the force plate even when camouflaged (Frederick and Henderson, 1970; Ratzlaff, 1982)

The Kaegi Gait Analysis System has been recently introduced in the United States. This system may be used to simultaneously record the forces exerted by all four feet of horses moving at the walk and trot (Auer and Butler, 1985). The instrumentation consists of a mat, 1.2 by 4 m, containing a series of 160 hydraulic tubes, each connected to a piezoelectric sensor. As the horse walks and trots over this mat, the force exerted by each foot changes the hydraulic pressure within the tubes which results in changes in voltage of the piezoelectric sensors. These voltage changes are recorded and analyzed by computer. The disadvantages of this system are the high initial costs, complexity of operation, inability to separate the horizontal force components from the vertical components, and forces from only one stride may be recorded.

Several attempts have been made to measure the vertical forces using hoof-mounted devices. Frederick and Henderson (1970) designed, constructed, and tested a horseshoe containing preloaded transducers. This shoe was bulky, thick, and heavy. The vertical forces exerted by the right front limb were recorded as a pony walked, trotted, and galloped on grass, hard soil, and pavement. The effects of this shoe on locomotion were not discussed. Pratt (1980a) constructed an instrumented shoe using separate force sensors on the inside and outside rim of the horseshoe. This shoe was used to record force patterns from the left front limb of a horse as it galloped on a training track. The sensors were not calibrated and the resulting force-time curves were not similar in shape to those obtained from force plate studies. A similar shoe was used in a study by Rubin and Lanyon (1982) to evaluate the changes in vertical force exerted by the left front limb of a pony moving at the walk, trot, and canter on a treadmill. The patterns of the force-time curves were similar to those obtained from the force plate studies; however, no units of force were reported.

To overcome the problems associated with force plates, the instrumented mat, and the earlier instrumented shoes, a system using a piezoelectric transducer mounted in an aluminum chassis welded to an aluminum horseshoe, was designed and tested (Ratzlaff *et al.*, 1985b). This system was used to measure the vertical forces exerted by the front feet during consecutive strides as the horses walked, trotted, cantered, and galloped on different surfaces.

Materials and Methods

The instrumentation consisted of specially constructed horseshoes, piezoelectric transducers, preamplifiers, analog integrator, and multichannel cassette tape recorder. Each horseshoe consisted of an aluminum racing plate (Thoro'bred Racing Plate Co., Inc., Anaheim, CA) with an aluminum transducer mount welded in place (Fig. 1,b). The transducer pocket, within this mount, was positioned over the center of the frog.

Each transducer (Fig. 1,d) consisted of a ceramic piezoelectric disc (EDO Corporation, Salt Lake City, UT), electrical leads (RG-178B, Alpha Wire Corporation, Elizabeth, NJ), polycarbonate discs (Lexan Products Division, General Electric Company, Pittsfield, MA), and a stainless steel disc. These components were bonded together with epoxy cement (Devcon Corporation, Danvers, MA) and molded in a dense polyurethane polymer (Hysor HO 7090, Washington Color and Chemical, Seattle, WA). The assembled transducer measured 0.2 inches (5.1 mm) in thickness and 0.7 inches

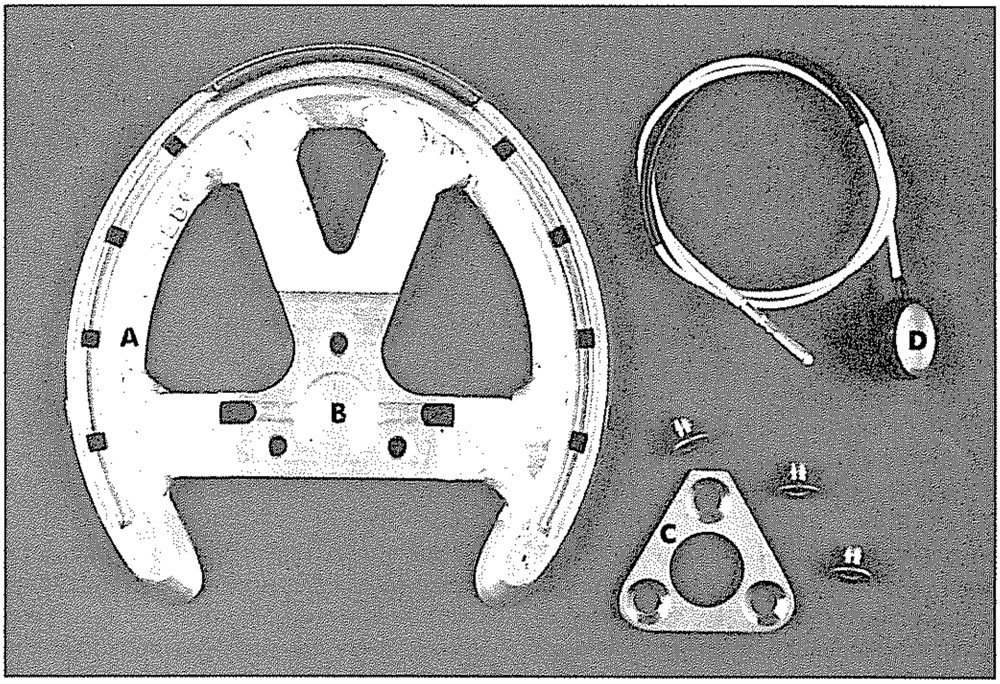

FIGURE 1 Components of the instrumented shoe A = conventional aluminum racing plate, B = transducer mount, C = mounting ring, and D = transducer

(17.8 mm) in diameter and weighed 9.5 gm, including the lead wire and connector. The ground contact surface of the stainless steel disc was 0.5 inches (12.7 mm) in diameter. Each transducer was calibrated under dynamic loads from 0 to 80 pounds (356 N). For all transducers, the calibration was linear through this range of loading.

The four-channel analog integrator (Technical Services, Washington State University, Pullman, WA) functioned as a charge amplifier. It converted the output from the piezoelectric element into a voltage that was proportional to the force applied to the transducer.

The instrumented shoes (Fig. 2), which weighed 40 to 45 gm more than the aluminum racing plate, were nailed to the hooves using standard farriery techniques. The cables from each transducer were taped securely to the legs and connected to the integrator which was mounted on the saddle pad. The integrator was cabled to a tape recorder (TEAC R-61 Cassette Data Recorder, B. J. Wolfe Enterprises, North Hollywood, CA) carried in a backpack by the rider.

To date, four conditioned Thoroughbred horses (Table 1) have been used in this study. Simultaneous recordings of the vertical forces exerted on the transducer on all four feet were obtained from consecutive strides of each horse as it galloped on the straightaways and turns of a one-half mile (0.8 km) research track (Hitchcock Equine Research Track, Washington State University, Pullman, WA). This track consists of short straightaways and symmetrical turns composed of long transitional curves of gradually changing radii into and out of the center of each turn. The banking gradually

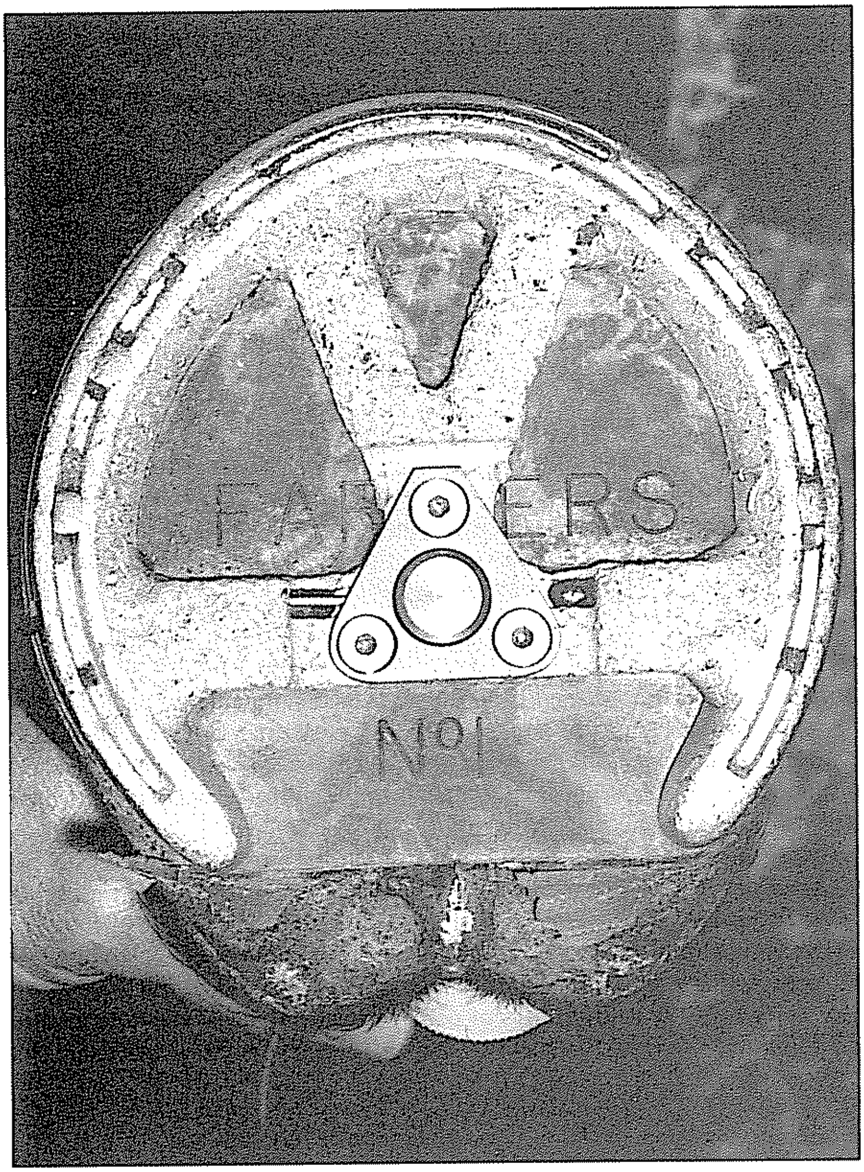

FIGURE 2. Assembled instrumented shoe nailed to the right front hoof

increases from 2% in the straightaways to 15% in the center of the turns. The cushion and base is a sandy loam soil (Table 2). The track was harrowed to a depth of one and one-half inches (3.8 cm) before each trial. The moisture content of the cushion was determined from samples taken from the top two inches (5.1 cm) of the track surface immediately after each trial.

Each horse was conditioned to the track by walking and trotting for at least one mile prior to each test. The speed of each horse galloping on the straightaways and turns

TABLE 1 Signalment of the horses.

Horse	Sex*	Age	Weight (lbs/kg)
1	F	3	974/383
2	G	7	1103/434
3	G	2	1080/425
4	G	2	1047/412

*F = female, G = gelding.

was determined by timing the horse with a stopwatch over a distance of one-eighth of a mile (201 m).

Permanent copies of the data from each tape were made using an oscillographic recorder (Model 1508B, Honeywell, Inc., Denver, CO). The force-time curves from six consecutive strides of each horse galloping on the straightaways and turns were digitized and analyzed by a computer program (Bioquant II, V. 2.1, 1984; R and M Biometrics, Nashville, TN) to determine the peak vertical forces and time components of the stride for each limb.

Results

Typical force-time curves obtained from the transducers mounted in each shoe of horse 3 galloping on the straightaway are shown in Fig. 3. In most sequences, the force patterns for each hoof were similar for repetitive strides. A sharp rise in vertical force occurred immediately following hoof contact, and peak force was attained during the middle of the support period for each limb.

The vertical forces exerted by the four horses galloping on the straightaway are summarized in Table 3. The actual forces, expressed in pounds, were the mean vertical forces exerted on the ground contact surface of the transducer [0.20 in^2 (1.27 cm^2)]. The greatest vertical forces were exerted by the lead forelimb followed by the lead rear, non-lead fore, and non-lead rear limbs, respectively.

Some variations in the realtionships of peak vertical forces between the lead rear and non-lead forelimb occurred for horse 3. No differences in the relationships of peak

TABLE 2. Soil composition of the cushion and base of the research track.

	Straight	Turn
Coarse sand*	40.0	41.2
Medium sand*	21.7	22.0
Fine sand*	15.3	15.1
Very fine sand*	4.6	4.9
Silt and clay*	18.4	16.7
Organic matter†	2.2	3.3

*Percentages determined by weight.
†Percentage determined by volume.

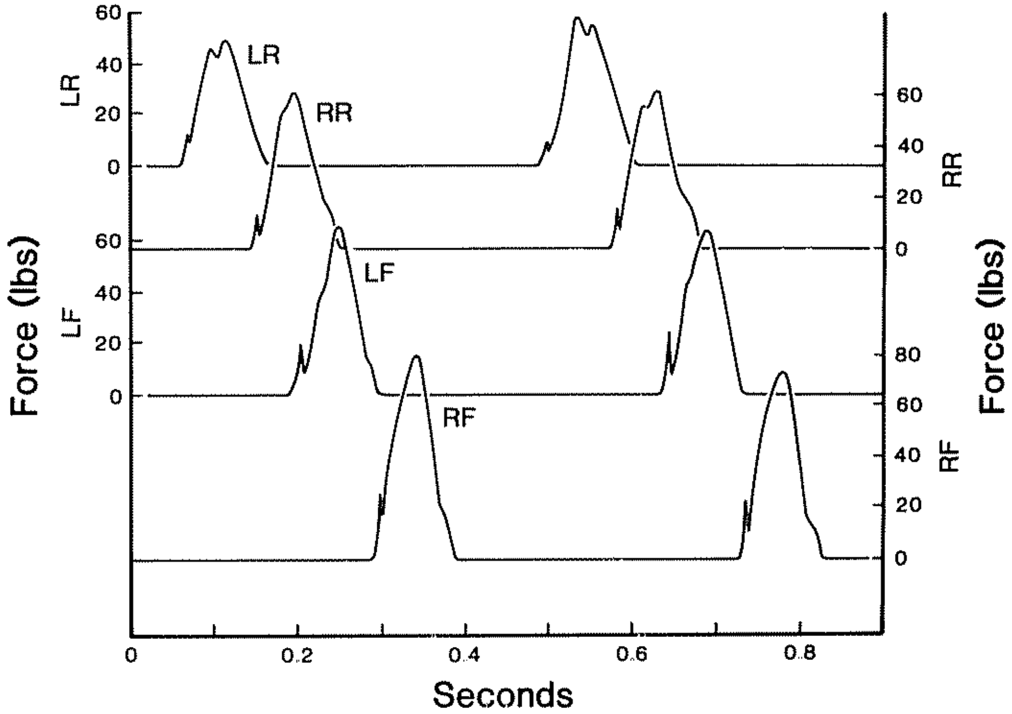

FIGURE 3. Force-time curves of two consecutive strides of horse 3 galloping in the straightaway. Force is that exerted in pounds on the contact surface of the transducer (1 lb = 4.45 N). LR = left (non-lead) rear, RR = right (lead) rear, LF = left (non-lead) front, and RF = right (lead) front.

vertical forces exerted by the four feet were noted between those horses galloping in a clockwise direction (horses 1 and 2) and those galloping counter-clockwise (horses 3 and 4) on the straightaway. In addition, no major differences in the force patterns were observed among these horses.

Variations in the peak vertical forces occurred between successive strides for each limb. This was reflected by the wide ranges, standard deviations, and standard errors of the means for these values (Table 3).

The average velocities, and the mean support and stride times of the horses galloping on the straightaway are presented in Table 4. Only minor variations in the mean support and stride times occurred between successive strides. No relationships between peak vertical forces or percentage of the total force and average velocities, support times, or stride times could be identified.

The time components (support, stance, and suspension times) of two successive strides of each horse galloping on the straightaway were determined from the force-time records. These stride components for horse 3 are shown in the top of Fig. 4. Minor variations in these times between successive strides were observed.

The force-time curves from all four feet of horse 3 galloping in the turn are shown in Fig. 5. The force patterns of the forelimbs and the lead rear limb were similar to

TABLE 3. Mean force and mean percentage of total force of the horses galloping in a right lead through the straightaway

	Mean force*	Range*	S.D.*	S.E.*	Mean % force**	Range**	S.D.**	S.E.**
Horse 1‡								
RF	59	55–63	3.4	1.4	30.5	28.8–32.5	1.4	0.6
LF	42	39–45	2.3	0.9	21.6	20.1–22.1	0.8	0.3
RR	52	47–56	3.1	1.3	26.9	24.5–27.9	1.4	0.6
LR	41	38–42	2.0	0.8	21.0	20.0–21.9	0.7	0.3
Horse 2‡								
RF	85	78–89	4.6	1.9	29.3	28.1–30.1	0.7	0.3
LF	67	62–78	5.9	2.4	22.9	21.7–24.6	1.0	0.4
RR	76	69–82	4.6	1.9	26.1	24.6–27.2	0.9	0.4
LF	63	61–72	5.0	2.0	21.7	20.3–22.8	1.1	0.4
Horse 3†								
RF	63	47–80	12.1	4.9	28.1	25.2–33.4	3.8	1.5
LF	57	49–65	5.9	2.4	25.6	21.4–29.4	2.8	1.1
RR	53	32–68	13.1	5.4	23.7	16.2–30.4	5.6	2.3
LR	50	39–64	9.7	4.0	22.5	18.9–29.3	3.9	1.6
Horse 4†								
RF	73	63–90	9.5	3.9	29.2	24.6–33.4	3.3	1.3
LF	58	47–76	10.0	4.1	23.3	18.4–30.4	4.5	1.8
RR	72	59–91	10.3	4.2	28.8	23.2–32.4	3.5	1.4
LR	47	41–56	6.5	2.7	18.7	17.0–22.8	2.2	0.9

*Pounds on the transducer (1 lb = 4.45 N).
**Percent of total force from all transducers
‡Galloping clockwise
†Galloping counterclockwise

RF = right front
LF = left front
RR = right rear
LR = left rear

those obtained from this horse galloping in the straightaway (Fig. 3). Spikes were present immediately following hoof contact, and peak forces occurred near the midpoint of the support phase of each limb.

The mean peak forces and percentages of the total force of all four feet of the horses galloping in the turn are presented in Table 5. The mean peak vertical forces and percentage of the total force were greatest for the lead forelimb followed by the non-lead fore, lead rear, and non-lead rear limb, respectively. These relationships were consistent between horses and were unaffected by the direction of travel of the horses through the turn.

Wide ranges in peak forces and percentages of total force occurred in successive strides. These resulted in large standard deviations and standard errors of the means (Table 5).

The average velocities, and the mean support and stride times of the horses galloping in the turns are presented in Table 6. Minor variations in the mean support and stride times for the individual limbs were observed between successive strides. The direction of travel of the horses through the turn had no apparent effect on these times.

TABLE 4. Average velocities, mean support, and mean stride times of the horses galloping in a right lead through the straightaway.

	Average velocity*	Mean support**	S.D.**	S.E.**	Mean stride**	S.D.**	S.E.**
Horse 1‡	14.4						
RF		111	1	0	434	2	1
LF		125	2	1	432	3	1
RR		116	4	2	430	3	1
LR		111	1	0	431	1	0
Horse 2‡	15.8						
RF		103	1	0	452	2	1
LF		104	1	0	452	2	1
RR		105	1	0	451	1	0
LR		106	0	0	451	1	0
Horse 3†	14.7						
RF		104	2	1	438	2	1
LF		101	3	1	438	6	2
RR		108	5	2	436	4	2
LR		113	7	3	436	9	4
Horse 4†	13.7						
RF		131	7	3	489	8	3
LF		129	7	3	490	11	4
RR		137	6	2	485	5	2
LR		132	10	4	485	11	5

*Meters/second.
**Milliseconds.
‡Galloping clockwise
†Galloping counterclockwise.

RF = right front
LF = left front.
RR = right rear.
LR = left rear.

The temporal components (support, stance, and suspension times) of two successive strides of horse 3 galloping in the turn are shown in the bottom of Fig. 4. These times were obtained from the force-time curves of the four hooves. Only minor variations in these time components occurred between successive strides.

The relationship of moisture content of the cushion to variations in peak forces of the horses galloping on the straightaway is presented in Fig. 6. As the moisture content increased, the variation in peak forces on the limbs between successive strides decreased.

Discussion

The techniques used in this study have several advantages over the methods previously used to measure vertical forces. This method provides a means to simultaneously measure the vertical forces exerted by all four feet of horses moving at various gaits with minimal effects on the normal locomotor patterns. Continuous recordings of the vertical forces exerted during consecutive strides can be obtained. In addition, the temporal components of repetitive strides can be measured.

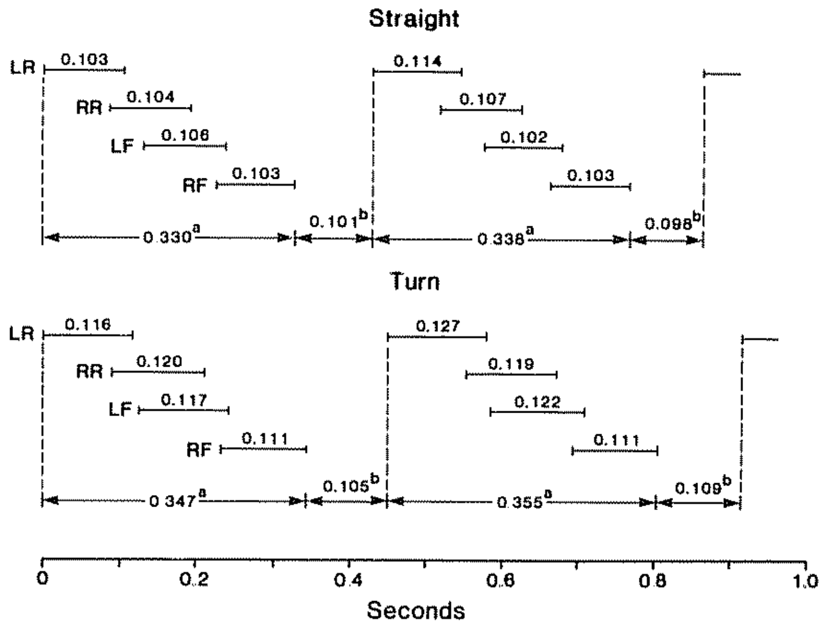

FIGURE 4. Temporal components of two consecutive strides of horse 3 galloping in a right lead on the straightaway (top) and turn (bottom). a = stance time, b = suspension time. LR = left (non-lead) rear, RR = right (lead) rear, LF = left (non-lead) front, and RF = right (lead) front.

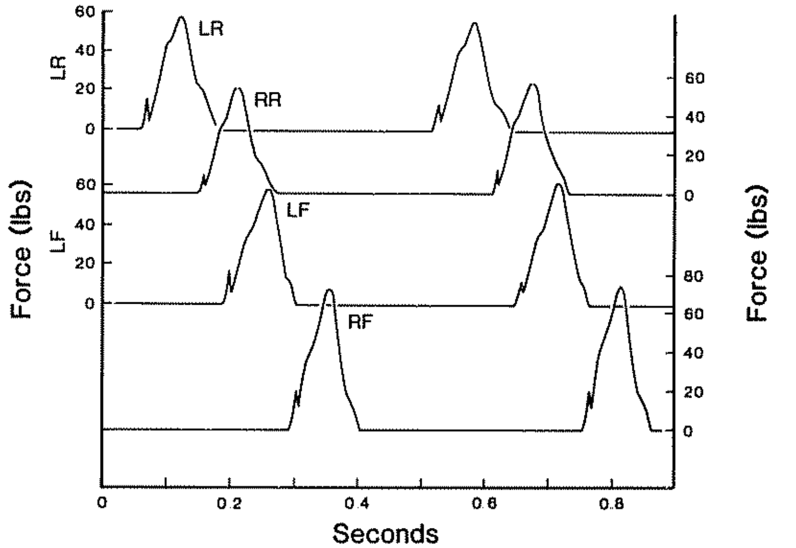

FIGURE 5. Force-time curves of two consecutive strides of horse 3 galloping in the turn. Force is that exerted on the contact surface of the transducer (1 lb = 4.45 N). LR = left (non-lead) rear, RR = right (lead) rear, LF = left (non-lead) front, and RF = right (lead) front.

TABLE 5. Mean force and mean percentage of total force of the horses galloping in a right lead through the turn.

	Mean force*	Range*	S.D.*	S.E.*	Mean % force**	Range**	S.D.**	S.E.**
Horse 1‡								
RF	59	53–65	4.6	1.9	31.4	27.9–33.3	1.9	0.8
LF	48	43–52	3.5	1.4	25.7	24.1–26.8	1.0	0.4
RR	43	38–46	2.7	1.1	22.7	22.1–24.3	1.2	0.5
LR	38	32–41	3.9	1.6	20.2	18.1–22.1	1.4	0.6
Horse 2‡								
RF	83	76–93	6.1	2.5	28.7	27.4–31.1	1.4	0.6
LF	73	69–77	2.7	1.1	25.2	23.7–26.3	1.1	0.4
RR	70	64–75	4.1	1.7	24.2	22.8–25.3	1.2	0.5
LR	63	59–68	3.1	1.3	21.9	20.1–22.7	1.1	0.5
Horse 3†								
RF	66	55–81	8.4	3.4	29.8	26.8–32.4	2.2	0.9
LF	64	59–65	3.3	1.4	29.1	26.3–31.5	2.0	0.8
RR	49	35–63	10.1	4.1	21.8	17.2–24.6	2.9	1.2
LR	43	36–50	5.3	2.2	19.3	17.6–21.1	1.2	0.5
Horse 4†								
RF	73	63–84	8.0	3.3	30.5	26.3–35.1	3.4	1.4
LF	60	54–65	3.8	1.5	25.0	23.8–25.9	0.7	0.3
RR	56	47–64	6.6	2.7	23.1	18.8–25.2	2.4	1.0
LR	52	39–60	8.1	3.3	21.4	17.9–25.0	3.0	1.2

*Pounds on the transducer (1 lb. = 4.45 n).
**Percent of total force from all transducers.
‡Galloping clockwise
†Galloping counterclockwise.

RF = right front.
LF = left front.
RR = right rear.
LR = left rear.

The center of the frog of the hoof was chosen as the site for the location of the transducer after a series of tests measuring the vertical forces on other locations. This site provided the most consistent records of vertical force exerted by the front hoof after consecutive strides on a variety of surfaces. The force-time curves obtained from this location were nearly identical to that reported for a single hoof strike of the lead forelimb of a horse galloping over a force plate (Kingsbury *et al.*, 1978).

The conditioning period before testing minimized the effects of the cables and tape on normal locomotion. No abnormal locomotor movements were observed during the trials. This was expected since earlier studies using the instrumented shoes (Ratzlaff *et al.*, 1985b) and electrogoniometry (Ratzlaff, 1980; Ratzlaff *et al.*, 1982) indicated that the cables and tape had no effect on normal locomotion of horses moving at the faster gaits.

The results from this study should be considered as preliminary information since only four horses were used. Substantially more data from many more horses will be required before significant conclusions can be made on the relationship of locomotor forces to velocity, temporal components of the stride, track surfaces, turns, or lame-

TABLE 6. Average velocities, mean support, and mean stride times of the horses galloping in a right lead through the turn.

	Average velocity*	Mean support**	S.D.**	S.E.**	Mean stride**	S.D.**	S.E.**
Horse 1‡	15.2						
RF		104	3	1	406	2	1
LF		106	2	1	406	4	2
RR		106	2	1	404	5	2
LR		102	2	1	403	3	1
Horse 2‡	13.3						
RF		117	3	1	517	5	2
LF		114	1	1	516	5	2
RR		119	0	0	517	5	2
LR		117	2	1	512	0	0
Horse 3†	13.6						
RF		119	1	1	479	6	2
LF		116	3	1	481	7	3
RR		124	4	2	479	6	3
LR		126	9	4	478	0	4
Horse 4†	14.2						
RF		122	2	1	477	6	2
LF		119	3	1	477	10	4
RR		126	5	2	479	9	4
LR		125	5	2	476	9	4

*Meters/second.
**Milliseconds.
‡Galloping clockwise.
†Galloping counterclockwise

RF = right front.
LF = left front.
RR = right rear.
LR = left rear.

nesses. However, once these data are obtained from significant numbers of horses, this method may be used as an in vivo system for measuring the consistency of track surfaces and the effects of turns on locomotor forces of horses moving on individual race tracks.

The variations in peak forces which occurred between successive strides appeared to be unrelated to the temporal components of the stride. These changes were probably associated with the physical characteristics of the track. The variations were similar to data obtained from a hoof-mounted accelerometer on horses galloping on different tracks (Pratt, 1980b). There also appears to be an inverse relationship between the moisture content of the track cushion and the amount of variation in peak force between successive strides. However, additional studies need to be conducted to adequately define this relationship.

The one-half mile (0.8 km) research track used for this study is significantly different from a traditional race track. Its construction was based upon the design proposed by Fredricson *et al.* (1975). The configuration of this track is designed to minimize the effects of turns upon the locomotion of horses galloping at high speeds. Because of

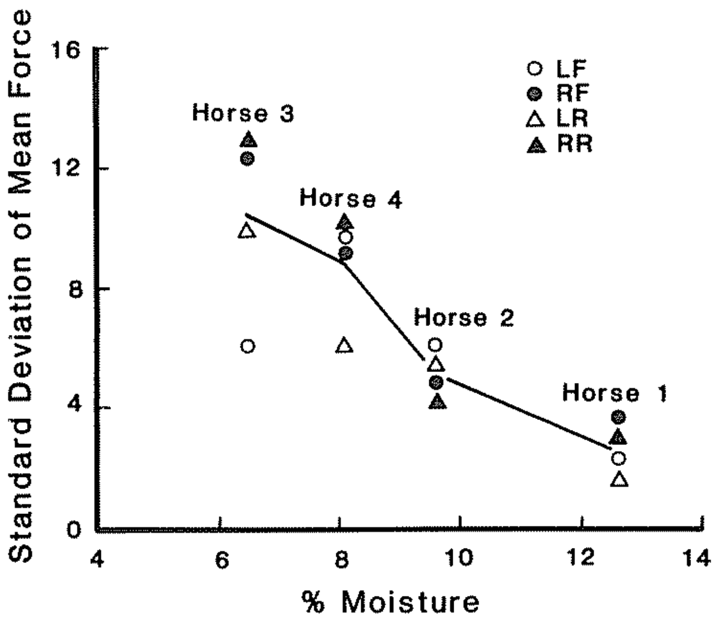

FIGURE 6. Relationship of moisture content of the cushion to the standard deviations of the mean peak vertical forces exerted by the limbs of horses galloping in the straightaway. LF = left front, RF = right front, LR = left rear, and RR = right rear.

this design, it is difficult to make comparisons of the locomotor parameters of horses moving through the turns of this track and those tracks constructed in the traditional manner. For example, horses galloping through the turns of the research track do not need to change leads to properly negotiate the turns. Therefore, any conclusions based upon the results of this study on the effects of turns on locomotor forces may not be applicable to other track designs. It is probable that the distribution of locomotor forces between the four limbs would be different on the turns of a traditional track.

The consistently greater vertical forces exerted by the forelimbs of horses galloping through the turn may help to explain the propensity for forelimb injuries in racing Thoroughbreds. It is expected that the disparity between the peak vertical forces exerted by the forelimbs and hind limbs would be even greater on tracks in which the turns had lower banking. This would further increase the potential for foreleg injuries.

Acknowledgment

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