Evaluation of ground reaction forces produced by chickens walking on a force plate

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Objective—To evaluate the use of a force plate as a method for objective gait analysis in adult poultry, to characterize ground reaction forces (GRFs) produced in adult chickens during normal walking, and to assess the variability of GRFs.

Animals—18 clinically normal 5-month-old Brown Leghorn hens

Procedure—Vertical, craniocaudal, and mediolateral GRFs were measured as hens walked across a standard force plate embedded in the middle of a runway.

Results—All GRFs were significantly affected by speed, and variability was high. With increasing speed, overall stance time decreased, but the percentage of stance time spent in braking or propulsion remained approximately equal. There was an overall increase in maximum propulsion force, which was produced at a greater rate over a shorter time; thus, propulsion integral decreased. Maximum braking forces and braking integrals were variable, but the rate at which the forces were generated increased. Mediolateral forces were 2 to 3 times greater in hens than values that have been reported for other species.

Conclusions and Clinical Relevance—A standard force plate can be used to objectively measure GRFs in walking adult hens; however, the large variation in the data suggests that the technique in its current form would be of limited clinical use. Overall, vertical and craniocaudal forces had similar characteristics to those of other species, whereas mediolateral forces were found to be much greater in chickens than for other species. (*Am J Vet Res* 2003;64:76–82)

Lameness is a major problem in the poultry industry, raising concerns about animals[1,2] and resulting in considerable economic losses.[3-5] Modern broilers have been selected for rapid growth rates to achieve a high final body weight and to produce more breast (pectoral) muscle, resulting in a dramatic change in body conformation when compared with birds that have not been genetically selected for those traits.[6-8] Although it is generally accepted that increased growth rates and body weight of modern poultry have a detrimental effect on locomotor ability, this has been difficult to prove conclusively. Some studies[9-12] have revealed a high correlation between body weight or growth rate and the incidence of skeletal abnormalities such as tibial dyschondroplasia, but other studies have not revealed a similar correlation.[13-15]

Modern broilers are generally quite inactive,[1,16] and there is considerable debate as to whether the altered gait and lack of activity are a result of the change in conformation or are attributable to pain.[17-20] In 1 study,[5] an increase in activity was detected following administration of an analgesic; however, a similar effect was not detected after administration of an analgesic in another study.[18] Many investigators assess lameness by use of the subjective Bristol gait scoring system.[17] A visual assessment is made of a bird's gait, and a score is allocated to each bird on the basis of a scale of 0 (normal) to 5 (able to move only by crawling or using the wings). Although widely adopted by industry because of its ease of use, there are obvious limitations to such a subjective method. Visual gait analysis is dependent on the skill and experience of the observers.[21] Repeatability is only moderately reliable,[22] and it allows only observation of movements, not forces. It was reported in 1 study[23] that the way a subject moves is an effect, rather than a cause, of the underlying problem. A more objective system is required to establish variables for a normal gait before attempting to determine the role of pain in various gait abnormalities.

Early objective methods of gait analysis in chickens involved the measurement of footprints made when birds with ink on their feet walked on paper.[24,25] More recently, efforts have concentrated on kinematic studies that used markers placed on specific anatomic landmarks[26]; however, inaccuracies can arise in marker position as a result of skin displacement or when a subject deviates from a plane parallel to the camera.

Locomotion is a complex biomechanical process that involves the body creating forces that are transmitted to the ground. **Ground reaction forces (GRFs)** have been measured in kinetic studies on a number of animals, including humans, and reveal clear changes following the onset of lameness.[27-30] If use of a limb elicits pain, or if a limb is biomechanically unsound, then a subject will be less willing to bear weight on it. Reassessing loading of a limb after administration of analgesics to a subject could provide an indication of whether pain plays a role in the initial lameness.[31]

Ground reaction forces have not been extensively investigated in adult chickens, although studies have been performed on clinically normal chicks at 1 to 2 and 14 days after hatching[32] as well as on chicks with incomplete spinal injuries.[33] Although investigators in those

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studies measured only vertical and horizontal forces, other authors have suggested that mediolateral force may be a good indicator of gait abnormalities.[34,35] Another set of experiments[a] has provided evidence that birds do not minimize their lateral movements effectively; thus, larger mediolateral forces should be produced during walking.

The objective of the study reported here was to evaluate use of a force plate as a method of objective gait analysis in adult poultry, to characterize and measure GRFs produced by hens during normal walking, and to assess the variability of GRFs.

Materials and Methods

Animals—Eighteen 5-month-old Brown Leghorn hens were used in the study. Hens were judged to be clinically normal on the basis of an orthopedic examination performed by a veterinarian prior to each testing session as well as gross postmortem examination performed at the end of the study. Hens were reared in mesh-floored battery cages and moved to a pen 2 weeks prior to testing. The floor of the pen was covered with approximately 20 cm of soft wood shavings. The pen was situated at 1 end of the testing runway with a small holding pen at the opposite end of the runway. A feeder and waterer were placed in the pen and holding pen, and hens were encouraged to explore and become familiar with the pens and runway. Hens were fed a pelleted feed formulated for layer hens.[b] Room light was provided by three bulbs (60 W/bulb; 14 hours light:10 hours dark), and a fluorescent strip light (15 W) was mounted above the force plate to provide additional light for the video cameras. Room temperature was maintained at 20°C, and relative humidity was maintained at approximately 50%.

Data collection—A force plate[c] was embedded in the middle of the 2.4-meter-long runway, which was enclosed by a solid wall on 1 side and a mesh fence on the other. The force plate was connected to an 8-channel charge amplifier[d] and junction box.[e] Range of the charge amplifier was selected automatically to suit the load (1,000 **picoCoulombs [pC]**/10 V); resolution for **vertical force (Fz)**, **craniocaudal force (Fy)**, and **mediolateral force (Fx)** was –7.8, –7.77, and –3.89 pC/N, respectively. Although sensitivity of the horizontal force measuring elements was twice that of the vertical force measuring elements, resolution when measuring the forces in each of the 3 main directions was the same. Sampling rate for the force plate was 100 Hz for a period of 2 seconds, and analogue signals were digitized by a converter in a personal computer[f] for processing by special software.[g] A camera[h] was positioned lateral to the force plate, and signals were recorded on a video recorder[i] that also affixed a time stamp to the videotape. Video sampling rate was 25 frames/s.

Hens were selected in random order and placed in the holding pen; hens were allowed to walk across the runway to the home pen. Only data for when a hen crossed the force plate in a straight line at a steady walking speed were saved for analysis. Because of technical problems with the force plate, data were collected for only 5 crossings/hen on the initial day of the study. Sixteen days later, data were collected for 10 crossings/hen. Data from both days were included in the analysis. Effect of the time lapse between these observation sessions was regarded as random and considered as such in the statistical analysis of the data. After collection of data for 5 suitable crossings, each hen was weighed by use of a balance[j] that was accurate to 0.1 g.

Gait variables—Several gait variables were measured in this experiment (**Appendix**). Speed was calculated from the videotape by use of frame-by-frame advance. A mesh grid of known dimensions was placed behind the runway, and a digital timer accurate to 0.1 seconds was placed in the field of view (frame rate, 25 frames/s). Although speed may have fluctuated between and within steps as a hen crossed the force plate, a wide range of speeds was used to assess the effect of speed on variability. Start and end points of a step or crossing were determined by manually positioning a cursor on the GRF tracing, and then the computer software automatically determined the various measurements within these points.

Data analysis—Forces were expressed as a percentage of each hen's body weight to enable comparisons to be made between birds of differing weights. By definition, maximum vertical force is always in excess of body weight, so this measurement was calculated as net of body weight before being expressed as a percentage. Certain measurements of steps were

Table 1—Median and mean values and coefficients of variation for ground reaction force (GRF) variables for pooled data of chickens crossing a force plate at any speed

Variable	Factor	CV-1	CV-2	Median	Mean	95% range for a new observation
Fz max – 100% (% bw)	Crossing	49*	44	32.5	36.1	12.2–86.4
Fz slope (bw/s)	Crossing	99*	75	8.4	11.8	1.3–54.0
Fy max (% bw)	Crossing	42*	36	30.2	32.8	12.3–73.6
Fy min (% bw)	Crossing	42*	39	25.3	27.4	10.7–59.4
Fx max (% bw)	Crossing	57	54	13.9	16.1	4.5–43.6
Fx min (% bw)	Crossing	64*	57	13.8	16.3	3.9–48.3
Y-ratio	Crossing	67*	59	1.19	1.14	0.31–4.55
X-ratio	Crossing	69	67	1.01	1.23	0.27–3.77
Speed (m/s)	Crossing	37†	34	0.56	0.593	0.262–1.184
Stance time (s)	Step	33†	30	0.32	0.336	0.162–0.628
Brake percentage (%)	Step	28	26	52.2	52.2	21.6–82.8
Braking rate (bw/s)	Step	76	70	1.6	2.02	0.38–6.73
Propulsion rate (bw/s)	Step	113†	102	6.55	9.86	0.93–46.03
Braking integral (bw • s)	Step	107†	94	0.0155	0.0227	0.0024–0.0987
Propulsion integral (bw • s)	Step	88	85	0.0154	0.0205	0.0031–0.0766

,†Bird or session component of variance differs significantly ($P = 0.01$; †$P < 0.05$) from zero.

CV-1 = Coefficient of variation between crossings for various hens and sessions. CV-2 = Coefficient of variation between crossings for the same hen and session. Fz max = Maximum vertical force. bw = Body weight. Fz slope = Rate of change of vertical force. Fy max = Maximum craniocaudal force. Fy min = Minimum craniocaudal force. Fx max = Maximum mediolateral force. Fx min = Minimum mediolateral force. Y-ratio = Ratio of maximum propulsion force to maximum braking force. X-ratio = Ratio of maximum lateral force to maximum medial force.

Table 2—The 95% ranges for a newly observed mean for GRF variables for pooled data of chickens crossing a force plate at any speed

Variable	Factor	Number of crossings/hen 5	10	15
Fz max – 100% (% bw)	Crossing	19.3–61.1	21.0–57.9	21.8–56.7
Fz slope (bw/s)	Crossing	2.5–38.3	2.7–36.7	2.8–36.2
Fy max (% bw)	Crossing	17.2–57.7	18.2–55.6	18.5–54.8
Fy min (% bw)	Crossing	16.2–43.5	17.5–41.0	18.1–40.2
Fx max (% bw)	Crossing	8.1–28.2	9.1–26.1	9.6–25.4
Fx min (% bw)	Crossing	7.0–32.4	7.8–30.4	8.1–29.7
Y-ratio	Crossing	0.56–3.12	0.61–2.93	0.64–2.88
X-ratio	Crossing	0.59–2.16	0.71–1.96	0.76–1.85
Speed (m/s)	Crossing	0.383–0.875	0.41 –0.826	0.424–0.808
Stance time (s)	Step	0.223–0.484	0.23 –0.462	0.242–0.454
Brake percentage (%)	Step	35.5–68.9	38.2–66.2	39.2–65.2
Braking rate (bw/s)	Step	0.83–4.04	0.97–3.68	1.03–3.57
Propulsion rate (bw/s)	Step	2.6–25.3	3.3–23.2	3.5–22.5
Braking integral (bw • s)	Step	0.0064–0.0566	0.0076–0.0514	0.0082–0.0500
Propulsion integral (bw • s)	Step	0.0084–0.0407	0.0103–0.0354	0.0113–0.0336

See Table 1 for key.

Table 3—Median and mean values, coefficients of variation, and 95% ranges for GRF variables for chickens crossing a force plate at various speeds

Variable	CV-1	CV-2	Speed	Median	Mean	95% range for a new observation
Fz max – 100 % (% bw)	45*	38	Fast	49.9	54.7	19.8–125.5
			Medium	32.3	35.4	13–80.2
			Low	25.0	27.5	10–62.7
Fz slope (bw/s)	89*	71	Fast	15.2	20.3	2.7–85.5
			Medium	8.4	11.3	1.5–46.9
			Low	6.5	8.8	1.2–36.6
Fy max (% bw)	37*	32Fast	41.6	44.3	18.8–91.6	
			Medium	31.1	33.2	14.2–68.1
			Low	26.3	28.0	12.0–57.7
Fy min (% bw)	41†	36	Fast	25.6	27.7	10.6–61.7
			Medium	28.4	30.8	11.9–68.0
			Low	20.3	22.0	8.4–48.7
Y-ratio	64*	53	Fast	1.64	1.94	0.44–6.08
			Medium	1.08	1.28	0.30–3.96
			Low	1.28	1.51	0.35–4.71
Fx max (% bw)	55	53	Fast	22.1	25.3	7.3–67.1
			Medium	15.0	17.1	5.0–44.7
			Low	10.9	12.5	3.6–32.9
Fx min (% bw)	55	53	Fast	21.5	24.6	7.1–65.4
			Medium	13.9	15.9	4.6–41.7
			Low	10.4	11.9	3.5–31.6
X-ratio	73	70	Fast	1.01	1.25	0.25–4.10
			Medium	1.06	1.32	0.27–4.26
			Low	1.04	1.29	0.26–4.21

Speed had a significant ($P = 0.01$) effect on median values for all variables except the X-ratio. Speed ranges were as follows: fast, 0.793 to 1.049 m/s; medium, 0.473 to 0.729 m/s; and low, 0.153 to 0.409 m/s.

See Table 1 for key.

expressed as a percentage of total stance time. On the basis of results of other experiments,[a] speed ranges were classified as follows: fast, 0.793 to 1.049 m/s; medium, 0.473 to 0.729 m/s; and low, 0.153 to 0.409 m/s. For measurements made on > 1 step/crossing, only 1 step was chosen at random for analysis to avoid possible sampling bias and serial correlation between steps in the same crossing. All measurements except those for brake percentage were positively skewed with a tendency for within-hen SD to increase with the mean. Accordingly, logarithmic-normal distributions more accurately described variation. Therefore, data were logarithmically transformed before analysis by use of the restricted maximum likelihood procedure[36] to produce estimates of means and variances. Variation in brake percentage was better described by a normal distribution in the percentage scale; therefore, it was analyzed without prior logarithmic transformation.

The 95% ranges for new single transformed observations or means of transformed data were approximated in the logarithmic scale by use of Student-*t* distributions with 17 degrees of freedom (number of hens minus 1) to account for some of the sampling variation in the variance components. Limits of the ranges were then back transformed and multiplied by an empirical adjustment that linked the mean of logarithms to the mean of untransformed values.

Results

Data collection was straightforward, because the hens apparently were motivated to return to their

Table 4—Median and mean values, coefficients of variation, and 95% ranges for GRF variables for chickens crossing a force plate at various speeds, analyzed on the basis of each step

Variable	CV-1	CV-2	Speed	Median	Mean	95% range for a new observation
Stance time (s)*	22	22	Fast	0.250	0.256	0.156–0.402
			Medium	0.312	0.319	0.196–0.497
			Low	0.396	0.405	0.248–0.632
Brake percentage (%)	24	22	Fast	55.1	55.1	27.3–82.9
			Medium	53.4	53.4	26.1–80.8
			Low	51.8	51.8	24.3–79.3
Braking rate (bw/s)*	51	51	Fast	2.18	2.45	0.76–6.23
			Medium	1.78	2.01	0.64–5.00
			Low	1.00	1.13	0.36–2.83
Propulsion rate (bw/s)*	94	90	Fast	12.3	16.8	2.2–69.0
			Medium	7.5	10.3	1.4–40.9
			Low	4.0	5.5	0.7–22.3
Braking integral (bw • s)	80	74	Fast	0.0137	0.0176	0.0030–0.0626
			Medium	0.0173	0.0222	0.0039–0.0772
			Low	0.0152	0.0194	0.0034–0.0681
Propulsion integral (bw • s)	84	77	Fast	0.0153	0.0200	0.0031–0.0758
			Medium	0.0154	0.0201	0.0031–0.0740
			Low	0.0177	0.0232	0.0036–0.0862

*Within a variable, speed had a significant ($P = 0.01$) effect on the median values.

cohorts at the opposite end of the runway. However, 7 or 8 crossings were required to obtain 5 crossings with data valid for analysis. Initial analysis of the pooled data set was performed, and it subsequently was repeated with the data grouped into the 3 speed ranges. Values for the mediolateral forces were relatively large, compared with values for vertical and craniocaudal forces, with respect to those reported in other species.

Coefficients of variation were high for the pooled data, indicating that the measurements varied considerably even between crossings made by the same hen during a single session (**Table 1**). The 95% ranges for a new observation were large. Stance time and brake percentage had relatively lower coefficients of variation. The percentage of time spent in braking or propulsion during a single stance period appeared to be approximately equal; median braking and propulsion integrals were also approximately equal. Median propulsion rate was approximately 4 times the median braking rate.

Analysis of pooled data for the effect of a newly observed mean revealed large 95% ranges (**Table 2**). Increasing the number of crossings used to calculate values would not have reduced the ranges substantially. It was expected that differences in speed would cause high variability in the results, so the data were subsequently reanalyzed within defined speed ranges to test whether speed had an effect on median values. Although grouping the data into speed ranges reduced the coefficients of variation, the 95% ranges and coefficients of variation were still high between and within hens (**Table 3**). Speed had a significant effect on the median in all measurements except for the X-ratio. Median values for maximum vertical force, propulsion force, and vertical loading rate all increased with increasing speed. However, median value for maximum braking force was greatest in the medium speed range; therefore, the Y-ratio was lowest at medium speeds.

Coefficients of variation were reduced when measurements made on steps were analyzed within speed groups (**Table 4**). Most coefficients of variation were high except for stance times and brake percentage (and, therefore, propulsion percentage). Speed had a significant ($P = 0.01$) effect on median stance time, braking rate, and propulsion rate. Median stance time decreased with increasing speed, whereas median braking rate and median propulsion rate increased with increasing speed. Speed did not have a significant effect on median braking percentage (and, therefore, propulsion percentage) or on braking or propulsion integrals.

Discussion

Use of the force plate enabled objective measurement of GRFs in adult hens; however, variability in the measurements was high, and accuracy of the estimates was not greatly improved by increasing the number of crossings. Much of the variability in GRFs is believed to be attributable to fluctuations in speed as the subject crosses the force plate,[37] and speed had a highly significant effect on all measurements made on crossings except for the X-ratio in the study reported here. Other studies[38,39] have documented a positive correlation between speed and maximum vertical force but have failed to find a correlation between speed and mediolateral and craniocaudal forces. In agreement with studies on humans[40] and dogs,[37] coefficients of variation for the vertical and craniocaudal forces in the hens of the study reported here were lower than the coefficient of variation for the mediolateral forces.

Gait variables are most repeatable in humans walking at their natural speed.[40] Although the coefficients of variation in the study reported here were reduced when we compared measurements within speed ranges, there is always a degree of normal biological variability between limb loading in successive stance phases, even when a constant speed is maintained.[k]

Variability may have increased because of a short double-contact period in which both limbs were contributing to the GRF simultaneously, and the resultant GRF was an average. This would not affect maximum forces, however, because these are created with a single limb in ground contact. Preliminary trials in which we attempted to isolate areas of the force plate in an effort to have a single foot register as hens walked across it proved highly inefficient; an average of 10 attempts were required to produce a single valid trial, which would be likely to significantly increase the variability by inducing fatigue and frustration in the subjects. Although it is most desirable during force-plate analysis that a subject have a single limb in contact with the force plate at a time, other studies[32,33,41] have used the technique we described for gait analysis of birds. Two of those studies[33,41] include graphs that clearly reveal the double-contact period occurring for a relatively short proportion of each stride. This seems logical, because there is no reason that the forces from 1 foot would directly oppose those of the other foot to any substantial degree during normal walking.

It is also possible that some variability may have been introduced by subclinical disease. However, gross abnormalities were not found during postmortem examination of the hens.

The high variability found in the study reported here raises concerns that this technique may not be applicable to clinical investigations in poultry. However, it has been documented that maximum vertical force is 1 of the most useful indicators of lameness.[29,30] This variable had the lowest variability in our study. However, another study[a] that involved the use of 2 strains of broilers raised on 2 feeding regimens revealed significant differences in many GRF variables between the groups, as determined on the basis of growth rates and conformation, despite high variability and periods of double contact.

Median values for maximum vertical force recorded in our study were of a similar order of magnitude to those seen in walking quail[41] and walking humans (125 to 149.9% of body weight).[21,42] Total vertical force equals the force required to support the body weight (mass X gravity) plus the force required to produce vertical acceleration of the center of gravity during walking.[43] The shorter stance period in a moving subject means that the force has to be greater. Maximum vertical forces in the study reported here increased significantly with increasing speed, which was in agreement with reports for other species.[44,45]

Maximum propulsion forces increased significantly with increasing speed. However, the effect of speed on braking force was more variable. In humans, the greatest rate of energy generation across a joint occurs with plantar flexion of the ankle during the push-off phase of propulsion.[21] In contrast, braking force arises as friction stops a foot from sliding forward during early limb loading; thus, it would not tend to increase to the same extent with increasing speed. Lower braking forces at slow speeds could have resulted from a foot being decelerated prior to loading; as the speed becomes slower, it is likely stride length will be shorter and the stance phases longer. Thus, friction forces will be lower and the rate of change of momentum will be less. With increasing speed, step length increases, implying greater deceleration with each step, because forward deceleration of the center of gravity is greatest when the line from the center of gravity to the foot is more steeply inclined.[46]

The fact that the maximum propulsion force is of similar magnitude to the maximum vertical force (minus 100% of body weight) in the same speed range indicates an inefficient gait, because the force being applied to raise the center of gravity vertically is similar to the force used to move it forward. Although vertical excursions of the center of gravity initially increase as step length increases in walking humans,[46] various gait optimizations prevent this from becoming too extreme.[21] Thus, birds are either unable to make use of similar optimizations, or they have changes in their gait pattern (eg, their joints flex more, and they have more bounce in their gait at increasing speeds).

Mediolateral forces have been measured in other species but are considered to be less useful because of their relatively small size in comparison with vertical and craniocaudal forces. Various values have been reported, including < 5 to 8% of body weight in humans,[47] "small" in quail,[41] and 1.28 to 6% of body weight in dogs.[44,48] The large mediolateral forces in the hens of the study reported here identify 1 way in which the gait of birds differs dramatically from that of most other biped and quadruped species. The largest mediolateral force during a step is applied to accelerate the center of gravity toward the opposite side of the body, over the leg beginning its stance phase. Thus, during a straight crossing, the X-ratio is approximately 1. A combination of a narrowed walking base and gait optimizations such as lateral bending of the trunk effectively minimizes lateral excursions in most species. The greater the walking base, the greater the lateral excursion required and the more inefficient the gait.[21] When gait optimizations are effective, speed should have little effect on mediolateral forces. In the study reported here, however, mediolateral forces increased significantly with increasing speed, indicating an energy-inefficient gait.

As expected, stance time decreased significantly with increasing speed, which is in agreement with reports for other species.[21,45,49] Braking and propulsion rates increased significantly with increasing speed; however, the median propulsion rate remained 4 to 6 times as high as the braking rate. Although the main propulsion thrust in humans comes from rapid plantar flexion of the ankle,[21] GRFs are also affected by the action of other body segments such as leg swing and twisting of the trunk about the vertical axis as the arms swing out of phase with the legs.[21,23,50] Analysis of videotapes from the study reported here revealed that the hens extended their necks to bring the head forward with the leg swing, then they retracted the head back as the foot contacted the ground and weight was loaded onto it. This may be a form of gait optimization in chickens that will assist forward progression of the center of gravity.

The percentage of stance time spent in braking or propulsion was approximately 50% and did not change significantly with speed. This is in agreement with the results of another study[51] in which it was suggested that the change in speed is mainly attributable to a change in the rate of application of the propulsion force while the duration stays the same.[52] This was documented in the hens of our study.

The study reported here documented that a force plate can be used to objectively measure GRFs produced during walking by Brown Leghorn hens;

however, large variation in the data limits the usefulness of this technique in its current form. Although vertical and craniocaudal forces of chickens had characteristics similar to those of other species, mediolateral forces were found to be 2 to 3 times greater in the hens.

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[a] Corr SA. *Avian gait analysis*. PhD thesis, Department of Clinical Veterinary Studies, University of Glasgow, Glasgow, UK, 1999.

[b] Roslin layer pellets, Roslin Nutrition, Midlothian, UK.

[c] Model 9281B11 with solid A1 plate, Kistler Instruments, Hants, UK.

[d] 8-channel charge amplifier (type 5865C), Kistler Instruments, Hants, UK.

[e] Junction box (type 5606), Kistler Instruments, Hants, UK.

[f] 433s/L, Dell Computer, Berkshire, UK.

[g] Bioware, version 2.0, Kistler Instruments, Hants, UK.

[h] Pulnix TM–528A CCD camera with Comisar 8.5 mm lens, Sunnyvale, Calif.

[i] ModelAG67720, Panasonic, Secaucus, NJ.

[j] ModelBP340000, Sartorius AG, Goettingen, Germany.

[k] Merkens HW. *Quantitative evaluation of equine locomotion using force plate data*. PhD thesis, Department of Anatomy, University of Utrecht, Utrecht, The Netherlands, 1987.

Appendix

Gait variables for ground reaction forces of chickens crossing a force plate

Fz	Vertical force; largest of the 3 ground reaction forces
Fz max/Fz min	Maximum vertical force/minimum vertical force
Fy	Craniocaudal force; separated into braking (negative) and propulsion (positive) forces
Fy max/Fy min	Maximum craniocaudal force/minimum craniocaudal force
Y-ratio	Ratio of maximum propulsion force to maximum braking force
Fx	Mediolateral force; separated into medial and lateral forces
Fx max/Fx min during a crossing	Maximum mediolateral force/minimum mediolateral force during a crossing
Fx max/Fx min during a step	Maximum mediolateral force/minimum mediolateral force during a step
X-ratio	Ratio of maximum lateral force to maximum medial force
Integral	Area under the vertical force-time curve; it represents total load over time (also known as the impulse)
Slope	Rate of change of force
Stance time of a crossing	Interval from the point at which vertical force increases from zero as a hen steps onto the force plate until it returns to zero as the hen steps off the force plate
Stance time of a step	Interval from first contact of a foot until the same foot is lifted from the force plate; measured from the craniocaudal force tracing
Speed	Rate of crossing; calculated from the videotape by use of frame-by-frame advance
Brake percentage	Percentage of a single stance period spent braking; therefore, it is equal to 100 minus the percentage of single stance time spent in propulsion
Braking and propulsion rates	Rate of change of craniocaudal braking force or propulsion force, respectively, in 1 stance period
Braking and propulsion integrals	Area under force-time curve for braking phase or propulsion phase, respectively, of 1 stance period; equal to total load during the stance period

References

1. Sainsbury DWB. Broiler chickens. In: Ewbank R, Kim-Madslien F, Hart CB, eds. *The management and welfare of farm animals*. Herts, UK: Universities Federation for Animal Welfare, 1999; 235–249.
2. Stevenson P. *Lameness or leg weakness in broiler chickens: a resume of the latest scientific research*. Petersfield, UK: Compassion in World Farming Trust, 2000;1–8.
3. Thorp BH. Skeletal disorders in the fowl: a review. *Avian Pathol* 1994;23:203–236.
4. Bennett RM, Christiansen K, Clifton-Hadley RS. Direct costs of endemic diseases of farm animals in Great Britain. *Vet Rec* 1999;145:376–377.
5. McGeown D, Danbury TC, Waterman-Pearson AE, et al. Effect of carprofen on lameness in broiler chickens. *Vet Rec* 1999;144:668–671.
6. Lilburn MS. Skeletal growth of commercial poultry species. *Poult Sci* 1994;73:897–903.
7. Webster J. Chapter 8. Pigs and poultry. In: *Animal welfare: a cool eye towards Eden*. Oxford: Blackwell Science, 1994;155–156.
8. Corr SA, Gentle MJ, McCorquodale CC, et al. The effect of morphology on the musculoskeletal system of the modern broiler. *Animal Welfare, in press*.
9. Nestor KE, Bacon WL, Moorhead PD, et al. Comparison of bone and muscle growth in turkey lines selected for increased body weight and increased shank width. *Poult Sci* 1987;66:1421–1428.
10. Leterrier C, Nys Y. Composition, cortical structure and mechanical properties of chicken tibiotarsi: effect of growth rate. *Br Poult Sci* 1992;33:925–939.
11. Vestergaard KS, Sanotra GS. Relationships between leg disorders and changes in the behaviour of broiler chickens. *Vet Rec* 1999;144:205–209.
12. Kestin SC, Gordon S, Su G, et al. Relationships in broiler chickens between lameness, liveweight, growth rate and age. *Vet Rec* 2001;148:195–197.
13. Haye U, Simons PCM. Twisted legs in broilers. *Br Poult Sci* 1978;19:549–557.
14. Cook ME, Patterson PH, Sunde ML. Leg deformities: inability to increase severity by increasing body weight of chicks and poults. *Poult Sci* 1984;63:620–627.
15. Duff SR, Hocking PM. Chronic orthopaedic disease in adult male broiler breeding fowls. *Res Vet Sci* 1986;41:340–348.
16. Weeks CA, Danbury TD, Davies HC, et al. The behaviour of broiler chickens and its modification by lameness. *Appl Anim Behav Sci* 2000;67:111–125.
17. Kestin SC, Knowles TG, Tinch AE, et al. Prevalence of leg weakness in broiler chickens and its relationship with genotype. *Vet Rec* 1992;131:190–194.
18. Hocking PM. Assessment of the welfare of food restricted male broiler breeder poultry with musculoskeletal disease. *Res Vet Sci* 1994;57:28–34.
19. Gentle MJ, Corr SA. Endogenous analgesia in the chicken. *Neurosci Lett* 1995;210:211–214.
20. Pickup HE, Cassidy AM, Danbury TC, et al. Self selection of an analgesic by broiler chickens. *Br Poult Sci* 1997;suppl 38: S12–S13.
21. Whittle M. Chapter 4: methods of gait analysis. *Gait analysis. An introduction*. Oxford: Butterworth-Heinemann Ltd, 1991;130–172.
22. Krebs DE, Edelstein JE, Fishman S. Reliability of observational kinematic gait analysis. *Phys Ther* 1985;65:1027–1033.
23. Winter DA. Concerning the scientific basis for the diagnosis of pathological gait and rehabilitation protocols. *Physiother Can* 1985;37:319–324.
24. Sheets L, Hassanein RS, Norton S. Gait analysis of chicks following treatment with tri-ortho-cresyl phosphate in ovo. *J Toxicol Environ Health* 1987;21:445–453.
25. Farage-Elawar M. Enzyme and behavioural changes in young chicks as a result of carbaryl treatment. *J Toxicol Environ Health* 1989;26:119–131.
26. Abourachid A. Comparative gait analysis of two strains of turkey, *Meleagris gallopava*. *Br Poult Sci* 1991;32:271–277.
27. Gatesy SM, Biewener AA. Bipedal locomotion: effects of speed, size and limb posture in birds and humans. *J Zool* 1991;224:127–147.
28. Lord M, Reynolds DP, Hughes JR. Foot pressure measurement: a review of clinical findings. *J Biomed Eng* 1986;8:283–294.

29. Budsberg SC, Verstraete MC, Soutas-Little RW, et al. Force plate analysis before and after stabilization of canine stifles for cruciate injury. *Am J Vet Res* 1988;49:1522–1524.

30. Jevens DJ, DeCamp CE, Hauptman JG, et al. Use of force-plate analysis of gait to compare two surgical techniques for treatment of cranial cruciate ligament rupture in dogs. *Am J Vet Res* 1996;57:389–393.

31. Walker JL, Evans JM, Meade P, et al. Gait-stance duration as a measure of injury and recovery in the rat sciatic nerve model. *J Neurosci Methods* 1994;52:47–52.

32. Muir GD, Gosline JM, Steeves JD. Ontogeny of bipedal locomotion: walking and running in the chick. *J Physiol* 1996;493:589–601.

33. Muir GD, Katz SL, Gosline JM, et al. Asymmetric bipedal locomotion—an adaptive response to incomplete spinal injury in the chick. *Exp Brain Res* 1998;122:275–282.

34. Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *J Biomech* 1977;10;261–268.

35. Leach DH, Sprigings EJ, Laverty WH. Multivariate statistical analysis of stride-timing measurements of nonfatigued racing Thoroughbreds. *Am J Vet Res* 1987;48:880–888.

36. Patterson HD, Thompson R. Recovery of inter-block information when block sizes are unequal. *Biometrica* 1971;58:545–554.

37. Jevens DJ, Hauptman JG, DeCamp CE, et al. Contributions to variance in force-plate analysis of gait in dogs. *Am J Vet Res* 1993;54:612–615.

38. Barr AS, Dow SM, Goodship AE. Parameters of forelimb ground reaction force in 48 normal ponies. *Vet Rec* 1995;136:283–286.

39. Merkens HW, Schamhardt HC. Evaluation of equine locomotion during different degrees of lameness. I: lameness model and quantification of ground reaction force patterns of the limbs. *Equine Vet J* 1988;6(suppl):99–106.

40. Kadaba MP, Ramakrishnan HK, Wootten ME, et al. Repeatability of kinematic, kinetic and electromyographic data in normal adult gait. *J Orthop Res* 1989;7:849–860.

41. Clark J, Alexander RMcN. Mechanics of running by quail (*Coturnix*). *J Zool* 1975;176:87–113.

42. Betts RP, Franks CI, Duckworth T. Analysis of pressures and loads under the foot. Part I: quantitation of the static distribution using the PET computer. *Clin Phys Physiol Meas* 1980;1:101–112.

43. Collins JJ, Whittle MW. Impulsive forces during walking and their clinical implications. *Clin Biomech* 1989;4:179–187.

44. Riggs CM, DeCamp CE, Soutas-Little RW, et al. Effects of subject velocity on force plate-measured ground reaction forces in healthy Greyhounds at the trot. *Am J Vet Res* 1993;54:1523–1526.

45. McLaughlin RM Jr, Roush KJ. Effects of subject stance time and velocity on ground reaction forces in clinically normal Greyhounds at the trot. *Am J Vet Res* 1994;55:1666–1671.

46. Cavagna GA, Margaria R. Mechanics of walking. *J Appl Physiol* 1966;21:271–278.

47. Biewener AA. Overview of structural mechanics. In: Biewener AA, ed. *Biomechanics structures and systems, a practical approach*. Oxford: Oxford University Press, 1992;1–20.

48. Budsberg SC, Verstraete MC, Soutas-Little RW. Force plate analysis of the walking gait in healthy dogs. *Am J Vet Res* 1987;48:915–918.

49. Mann RA, Hagy J. Biomechanics of walking, running and sprinting. *Am J Sports Med* 1980;8:345–350.

50. Dillingham TR, Lehmann JF, Price R. Effect of lower limb on body propulsion. *Arch Phys Med Rehabil* 1992;73:647–651.

51. McLaughlin RM Jr, Roush KJ. Effects of increasing velocity on braking and propulsion times during force plate gait analysis in Greyhounds. *Am J Vet Res* 1995;56:159–161.

52. Wetzel MC, Stuart DG. Activation and co-ordination of vertebrate locomotion. In: Alexander R McN, Goldspink G, eds. *Mechanics and energetics of animal locomotion*. London: Chapman and Hall, 1977;115–151.