The measurement of ground reaction force in dogs trotting on a treadmill

An investigation of habituation

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Summary
We studied the time necessary to obtain reliable kinetic data from healthy dogs trotting on a treadmill. Ten adult male Malinois Belgian Shepherd dogs were made to trot on an instrumented treadmill to record the ground reaction force for the entire body and to determine the vertical force variables (peak [PFz], impulse [IFz], stride time [Str], peak time [Tz] and contact time [Ct]). Data were collected from each dog, during three sequences per day, on three consecutive days. In order to determine the contribution of the 'sequence', 'day of measurement', and 'dog' factors and the percentage of variance attributable to dogs, data were analyzed with a linear mixed model. The curve shapes were similar to those obtained with a floor-mounted force platform. Intra-dog coefficients of variation were between 1.57 and 3.46%. Inter-dog coefficients of variation were between 4.18 and 7.82%. A sequence effect was not noted. Each day had a significant effect on all of the data. All variables differed significantly from the first day compared to the other days. However there was not any difference between days 2 and 3. The percentage of the total variance attributable to dogs ranged from 37 to 88%. The coefficients of variation were lower than those obtained with common protocols. The treadmill locomotion remained consistent during a single session. Even if interday variation needs to be accounted for, reliable data can still be obtained after a single training session. The majority of the variation was attributable to the dog. An instrumented treadmill may be used for kinetic analysis.

Keywords
Kinetics, dog, treadmill, habituation, gait analysis

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Introduction

The force platform has become a benchmark for the quantitative assessment of canine locomotion. The development of information technology and electronics has made this non-invasive precision tool accessible, making it possible to achieve a more comprehensive understanding of motion. For optimized utilization of the force platform, the ability to rapidly obtain reliable and repetitive data is essential.

Ground reaction forces have been measured in dogs, in order to study normal and abnormal locomotion. These studies have made it possible to characterize the walking and trotting gaits of clinically healthy dogs of various breeds (1–4), describe the sources of variation of ground reaction force (5–9), demonstrate the redistribution of forces during episodes of lameness and evaluate the efficacy of orthopedic, medical or surgical treatments (10, 11).

In all of these studies, the most commonly used protocol has consisted of the dog being led on a leash by a handler on a platform containing a force plate. The distance covered is filmed and the velocity measured with photoelectric cells. The data are derived from the mean of several trials conducted on the same day.

It is obvious that results from a force platform are very reliable, provided that the recordings are made under conditions that reduce the sources of variation (12–15). The vertical force has been the most frequently studied; it has the greatest amplitude and the lowest variability (compared to amplitude) of the forces measured. The sources of variation identified by previous protocols include the following: velocity, gait, morphological parameters, intra- and inter-individual variation, the handler, training and pathological status.

We propose a modification to the traditional protocol by using a treadmill equipped with force sensors. Using a treadmill makes it possible to precisely identify the velocity of the dog as well as to keep this velocity constant throughout the entire recording process. The device makes it possible to record the ground reaction force for several seconds, and thus study results based on a large number of consecutive strides. The aim is to obtain a more continuous analysis of movement, which is particularly useful when studying the consistency of locomotion. Several studies describe the use of a treadmill in humans (16–18) as well as horses (19–21) and dogs. To our knowledge, there has not been a recent description of the use of an instrumented treadmill for a canine gait kinetics analysis.

The purpose of this study was to determine whether or not it was possible to achieve stabilization of the kinetic parameters, while the subject was trotting on a treadmill. Healthy dogs were studied over several consecutive days, and the alternative hypothesis of a significant intra-individual variation of vertical force was examined. The training time required to record reliable data was also determined.

Materials and methods

Dogs

Ten adult male Malinois Belgian Shepherds, aged two to six years and weighing 26

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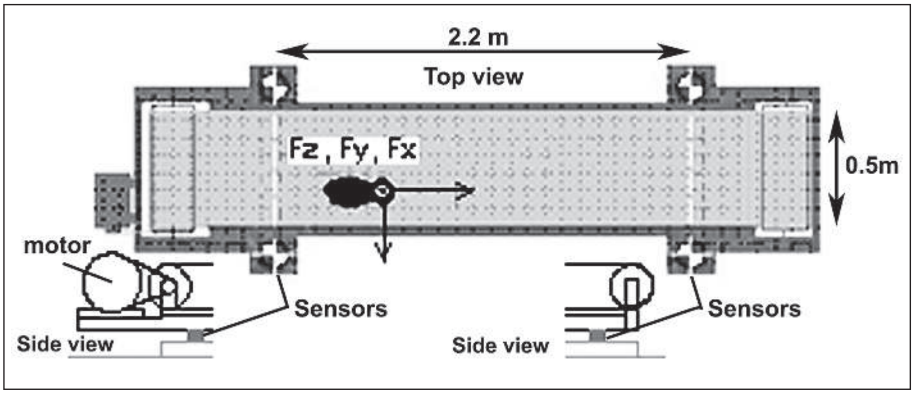

Fig. 1 Instrumented treadmill: the four force sensors situated under the treadmill make it possible to record the ground reaction force in the three planes (Fz, Fy, Fx).

to 34 kg were included in the study. The dogs were clinically healthy and did not have any history of orthopaedic problems and had been declared free from hip dysplasia by radiological diagnosis.

They had not been trained for locomotion on a treadmill, neither in the context of scientific analysis nor a simple physical training.

Instrumented treadmill equipped with force sensors

An instrumented single belt ADAL 3D-Run treadmill[a] with an effective surface of 2.2 m in length and 0.50 m in width, operated by a control panel and providing a velocity range of 0 to 7 m/s (precision of 0.028 m/s) was used. A control system enabled the actual belt velocity to be displayed in real time.

The treadmill was equipped with four force sensors, quartz transducers enabling the ground reaction force to be measured in three planes (mediolateral (Fx), craniocaudal (Fy) and vertical (Fz)). The sensors were situated directly on the ground, under the treadmill (Fig. 1).

The measurement system was connected to an amplifier, which was in turn connected to an IBM-compatible personal computer by a 16-bit data acquisition card (National Instrument NI-DAQ). System calibration was performed in the laboratory. The measurements were made using the Adirun® software program.

[a] TecMachine, Andrezieux Boutheon, France.

Protocol

Before each measurement, the sensors were reinitialized, and the animal weighed on the force platform.

Each dog was equipped with a support harness and kept on the treadmill by the handler who was situated above the treadmill but outside the force platform. The animal was encouraged to maintain a constant forward walking direction.

The data were recorded at 2.7 m/s. Each dog walked until the analysis velocity was attained. The dog then trotted for one minute, during which it grew accustomed to the movement of the belt. Data was not measured during this first minute. Once stable gait was observed by the operator and the handler, the signal was recorded at 500 Hz per channel for ten seconds. The signal was filtered at 50 Hz (low-pass filter). At least three non-consecutive sequences were recorded. Any recordings during which the dog stumbled or visibly changed gait were rejected. The complete analysis lasted 10-15 minutes for each dog.

This same analysis protocol was repeated for the same dog three days in succession (nine recordings per dog).

Data recorded

Each dog advanced on a single force platform during the analysis. The trot was chosen because of the succession of ground reaction forces involving a pair of diagonal legs. The ground reaction force was measured for the entire body.

The ground reaction force was measured in the three planes: Fx, Fy and Fz. The forces were normalized by relating their values to the weight of the subject (BW). Only Fz was analyzed statistically: peak PFz (%BW), impulse IFz (%BW.s), duration of stride Str (ms), time to peak Tz (related to the duration

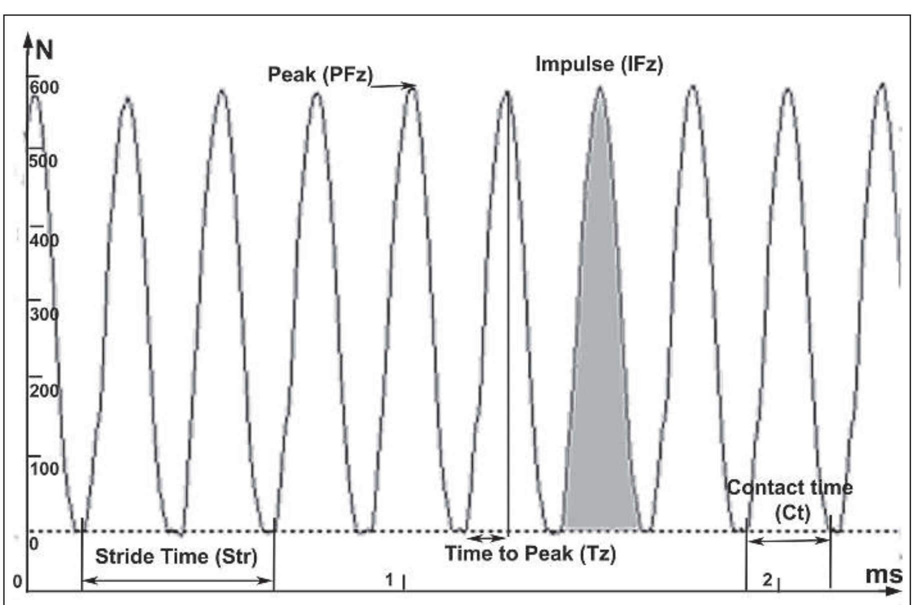

Fig. 2 Vertical force versus time. Variables used for the statistical analysis.

of stride %Str) and Contact time Ct (%Str) (Fig. 2). Fy and Fx were measured but were not analyzed statistically.

Data analysis

The data were analyzed using the MIXED procedure (22) SAS software[b]. The mean (M), standard deviation (SD), coefficient of variation (CV) and confidence interval at 95% (CI) were calculated for each variable, each dog, each day and each sequence. The means of each sequence were then analyzed by an analysis of variance test. Three factors were isolated: a 'sequence' factor at three levels, a 'day' factor at three levels and a 'dog' factor at ten levels. The means calculated were compared using a Student-Newman-Keuls test. The variance attributable to the dog (σ^2_D) and the residual variance were determined by setting mean squares equal to expected mean squares and solving for variance. The percentage of total variance attributable to the dog was calculated.

Results and statistical analysis

None of the dogs refused the exercise; only three proved to be refractory and showed signs of apprehension at the beginning of the experiments.

Holding the dog in position was not difficult. As the dog was encouraged to the front of the treadmill, the handler carried out minimal control, and the animal could even advance freely on the system. A modification related to holding the dog in position was not noted down in the data. The belt velocity was always 2.7 ± 0.05 m/s.

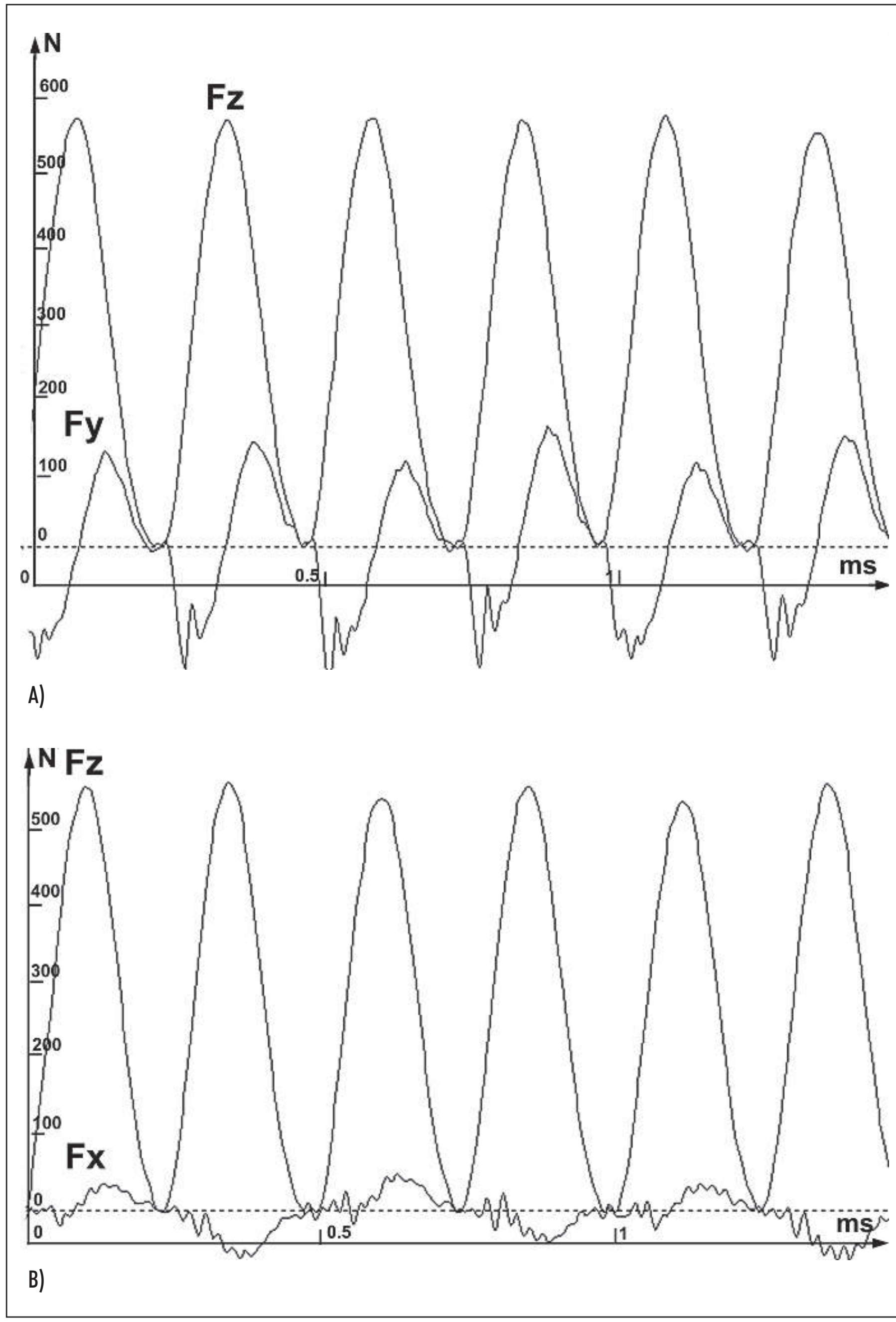

Fig. 3 A) Vertical force (Fz) and Craniocaudal force (Fy) versus time. Craniocaudal force is represented by a succession of sinusoids, the frequency of which is the same as vertical force. For each period of vertical force there is a negative phase followed by a zero-crossing synchronous with the peak of vertical force, followed by a positive phase. B) Vertical force (Fz) and Mediolateral force (F_{χ}) versus time. Mediolateral force is represented by a series of sinusoids with a frequency two times less than vertical force, with a minimum and maximum corresponding to the peak of vertical force and a zero-crossing during the aerial phase.

Qualitative analysis

For all dogs and all sequences, the same curve shapes were obtained for each of the directions of the ground reaction force (Fig. 3).

Vertical force (Fz) is represented by a succession of parabolas, corresponding to each two-limb strike (right forelimb-left hind limb or left forelimb-right hind limb). Each parabola corresponded to a stance phase, and the brief zero crossing point between each parabola corresponded to a short aerial phase.

For craniocaudal force (Fy) (Fig. 3A), a braking phase and a propulsion phase were observed. The zero-crossing point corresponded to the time of maximum bipodal stance. A peak at impact of remarkable amplitude was recorded.

[b] Mixed Proc, SAS Institute, Cary, NC, USA.

For mediolateral force (Fx) (Fig. 3B), a succession of parabolic pairs of Fz with Fx positive alternating with Fx negative was observed. A video analysis in 'real time' demonstrated that when Fx was positive, the foot strikes were right forelimb and left hind limb, and when Fx was negative, the foot strikes were left forelimb and right hind limb.

Fz was always the force of maximum amplitude, followed by Fy and then Fx. For Fx, amplitude was particularly low.

Quantitative and statistical analysis

Each recording included between 19 and 23 strides, depending upon the animal's size and ease of movement. For each curve, the means and standard deviations were calculated on all foot strikes. For each sequence, M, SD, CV and CI were calculated.

The combined means (all the sequences, days and dogs) are shown in Table 1. The data reported here differ from those usually described. Consecutive foot strikes have been taken into account, and stride duration was taken as a time marker. The same values were recalculated with the duration of the stance as a time marker. The mean value of contact time was Ct=201.48 ms, and the time of peak vertical force was Tz=46.93%Ct.

For all of the sequences, days and dogs, the inter-dog parameters (among dogs, all trials) were as follows: inter-dog SD, inter-dog CV and inter-dog CI (Table 2). By taking into account each dog for all the sequences and days, the same intra-dog parameters (within dogs, all trials) were calculated: intra-dog SD, intra-dog CV and intra-dog CI (Table 3).

Statistical analysis of variance

The total variance and the contribution of various factors were studied: 'sequence' factor, 'day' factor and 'dog' factor.

The contribution to variance of the 'sequence' factor for the same dog was not significant. There was no significant difference (α =5%) among the sequences for each variable. The contribution to variance of the 'day' factor for the same dog was significant ($P<0.05$) for all the recordings. However, there was a significant difference (α =5%) for all variables between day 1 and days 2 and 3, but there was no significant difference between days 2 and 3 for all variables. The contribution to variance of the 'dog' factor was significant and the greatest for all the data. The percentage of total variance attributable to the dog was calculated (Table 4).

Table 1 Means for all dogs.

Variable	Tz (%Str)	Str (ms)	Ct (%Str)	PFz (%BW)	IFz (%BW.s)
Mean	19.98	474.14	42.51	190.50	22.29

Table 2 Inter-Dog (all dogs on all days) descriptive statistics.

Variable	Tz (%Str)	Str (ms)	Ct (%Str)	PFz (%BW)	IFz (%BW.s)
StD	1.56	19.80	1.95	14.27	1.22
CV inter-dog	7.82 %	4.18 %	4.59 %	7.49 %	5.46 %
95% CI	± 0.97	± 12.27	± 1.21	± 8.85	± 0.75

Table 3 Intra-Dog (within dogs, among days) descriptive statistics.

Variable	Tz (%Str)	Str (ms)	Ct (%Str)	PFz (%BW)	IFz (%BW.s)
StD	0.69	7.66	0.67	4.00	0.53
CV intra-dog	3.46 %	1.61 %	1.57 %	2.13 %	2.37 %
95% CI	± 2.50	± 9.00	± 3.50	± 2.00	± 1.80

Table 4 Contribution of 'dog' factor to total variation.

Variable	Tz (%Str)	Str (ms)	Ct (%Str)	PFz (%BW)	IFz (%BW.s)
σ^2_D	2.0271	362.01	3.2896	136.40	0.5425
Residual Variance	0.6007	49.9602	0.7693	78.1902	0.9370
Percent variance	77 %	88 %	81 %	64 %	37 %

Discussion

Vertical force has often been described. Locomotion on a treadmill is different from locomotion on the ground (21, 23, 24). However, a treadmill is often used in humans or horses to study gait. The velocity used here was more elevated than those used normally. Two simultaneous stances were considered, which limits comparisons with previous studies. The study was carried out on Malinois Belgian Shepherds. To our knowledge, there has not been a previous report on kinetic analysis with this breed.

The results were compared with those from animals of a similar build and comparable velocity. All of the results were of the same order as those previously described, for contact time Ct as well as for time to peak of vertical force Tz. Regarding the peak PFz and impulse IFz, the sum of the values (7, 9) of both limbs was close to our data: for PFz, around 120% BW for a forelimb and 90% BW for a hind limb, for IFz around 14% BW/s for a forelimb and 9% BW/s, according to studies carried out at a slightly higher speed [2.7–3 m/s].

The video analysis provides an initial explanation, but future studies will be required to specify the contribution of each limb at a given moment. The contact time is shorter for the hind than for the forelimbs. It is uncertain whether the initiation of the foot strike is completely synchronous between the two limbs. The parabola obtained cannot be considered as the simple sum of two parabolas of identical phase and period.

The curve shapes are consistent with those described in the literature, showing the same phases and the same synchronism for the three forces. The shape of the Fx curve was very stable. This force was described as very variable in its amplitude and direction during sessions and with the various animals (4). In this study, the amplitude fluctuated, but the direction remained constant for each foot strike throughout the sessions with all animals. The variability recorded may be attributed to the repetition of trials and to the distinct and non-consecutive analysis of each foot strike.

The video recording in 'real time' made it possible to determine that the foot strikes for which Fx was positive corresponded to the 'right fore-left hind' foot strikes, and that the foot strikes for which Fx was negative corresponded to the 'left fore-right hind' foot strikes. This is compatible with a previous report about Fx (4): Fx is oriented towards the ipsilateral side with the limb put down, and the amplitude of Fx is greater for the forelimbs. The forelimb guided the direction of Fx.

A remarkable peak at impact was recorded on Fy. This peak has already been studied (2–4), but its explanation remains uncertain. In this study, its amplitude impeded the analysis of the preceding braking force and the impulse force following each impact.

The measurement of consecutive strides and velocity stabilization has made it possible to achieve better measurement repeatability and limited the variability for the same animal. The confidence intervals and coefficients of variation CV calculated were low. Typically (4,6,25,26), the intra-dog CV was close to 5% for PFz and close to 4% for IFz. In this study, 2.13% and 2.37% for PFz and IFz, respectively, were achieved (Table 3). For each variable, the inter-dog CV was low. To date, the CV has been described (4, 6, 25) as close to 8.5 to 10% for PFz and close to 7.5 to 11% for IFz. 7.49% and 5.46% for PFz and IFz, respectively, were calculated (Table 2). The inter-dog variability was reduced with the use of a treadmill.

Traditionally, the dog is led on a leash and left free to progress at its own speed, within the limit of a predefined gait (walk, trot, gallop) and a predetermined velocity range. In our study, the animal was forced to follow the belt running speed and advance at a velocity that may not have been familiar to it. The walking cycle was more variable at a forced speed than at a chosen speed. The choice of analysis velocity was therefore important: this velocity must enable each dog, whatever its size, to move forward in the best way possible, i.e. with as steady a gait as possible. This choice is therefore an important element to consider for future studies, particularly those using animals that are lame.

Constant velocity analyses make it possible to avoid velocity-related variability, but as a result there is a new source of variability: the animal's ease of movement (a function of the velocity itself and interactions between 'velocity-conformation'and 'velocity-integrity of locomotor function'). However, it is always desirable to reduce the velocity variations and accepted velocities ranges to the maximum, whatever the study objective (normal or abnormal locomotion).

Previous studies have shown that adaptation to treadmill locomotion is required (21, 23, 24, 27). In one study (27) by Buchner et al., horses moved forward on a treadmill. They were somewhat frightened during the initial strides, and then during the first few minutes tried to find their balance and optimum position (accommodation phase). Finally, they gradually became accustomed to it (habituation phase). These studies all agreed that recording reliable mechanical data requires avoiding the accommodation phase and having at least two training sessions.

The vertical force remained stable during a single analysis session for all the sessions. As no data was measured during the first minute after the analysis velocity is attained, no accommodation phase was noted down in the data. The 'day' factor had an effect in the total variation. The daily variation has already been described as significant (26), and our results confirmed this variation. However, the 'day' factor consolidated two parameters: the one intrinsic to the individual, the actual daily variation, and the other extrinsic, the habituation to locomotion on the treadmill. The protocol increased the effect of the daily variations by combining two types of different variations. Day 1 was significantly different from days two and three, but there was not any significant difference between days two and three. The dogs had become accustomed for locomotion on the treadmill, at least in part, from the second day.

Continuation of training remains questionable: How long will a dog remember this training? Will the same training be required if the same dog is studied a few weeks later? These questions are especially important for studies on efficacy and follow-up of surgical or medical treatments.

The major part of the variation remains attributable to the dog, being 64 to 88% according to the variable concerned. For IFz only, a low coefficient (37%) was calculated. This is to be compared with the low intra-and interdog coefficients of variation and thus a large homogeneity among animals. As a result, the 'dog' factor had a less predominant effect in the variation of IFz compared to the other factors ('sequence' and 'day'), compared to that same effect in the variation of the other variables. The real effect of the 'day' factor remains to be determined, and over a longer period than that used in this study. However, the test used differentiated the animals quite adequately.

Even if the data used here are not specific for a single limb because of two simultaneous stances, these results are a starting point with regard to the training required for dogs with a view to a kinetic analysis on a treadmill. The results of this study have made it possible to describe a new approach to canine kinetic analysis. The results are in keeping with the current literature and have been more repetitive. It would be an advantage to conduct a study over several days.

In conclusion, the treadmill appears to have application for gait analysis. The test for measuring ground reaction force is reproducible. Variation and variability were lower than that obtained with standard protocols. Our test is more repeatable. Moreover, it represents an immense saving in time and facilitates the experiments. Although the 'day' factor (habituation to the environment, the treadmill and residual intra-individual variation) requires subsequent research, a treadmill may be used to analyze the vertical component of the ground reaction force.

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As an exercise in diagnosis, V.C.O.T. intermittently publishes a radiograph or image "puzzle". The diagnosis and a short description is published on page 109.
The author of this section is H. Dobson, BVM & S, DVSc, MRCVS, Cert EO, DACVR. Radiologist - Ontario Veterinary College, University of Guelph, Canada.

What is it?

Number 47 – Question

A six-year-old Thoroughbred mare presented with an acute onset of bilateral nasal discharge, excess salivation and difficulty eating. Radiographs of the throatlatch region were made as a part of the clinical evaluation.