Measures of weight distribution of dairy cows to detect lameness and the presence of hoof lesions

M. Pastell
University of Helsinki

L. Hänninen
University of Helsinki

A. M. de Passillé
Agriculture and Agri-Food Canada

J. Rushen
Agriculture and Agri-Food Canada

Recommended Citation

Pastell, M., Hänninen, L., de Passille, A. M., & Rushen, J. (2010). Measures of weight distribution of dairy cows to detect lameness and the presence of hoof lesions. Journal of dairy science, 93(3), 954-960. DOI: https://doi.org/10.3168/jds.2009-2385

J. Dairy Sci. 93:954–960
doi:10.3168/jds.2009-2385

Measures of weight distribution of dairy cows to detect lameness and the presence of hoof lesions

M. Pastell,*†[1] L. Hänninen,†‡ A. M. de Passillé,§ and J. Rushen§
*Department of Agrotechnology, PO Box 28, 00014 University of Helsinki, Finland
†Research Centre for Animal Welfare, PO Box 57, 00014 University of Helsinki, Finland
‡Department of Production Animal Medicine, PO Box 57, 00014 University of Helsinki, Finland
§Agriculture and Agri-Food Canada, PO Box 1000, Agassiz, British Columbia, V0M 1A0, Canada

ABSTRACT

There is increasing interest in automated methods of detecting lame cows. Hoof lesion data and measures of weight distribution from 61 lactating cows were examined in this study. Lame cows were identified with different numerical rating scores (NRS) used as thresholds (NRS >3 and NRS ≥3.5) for lameness. The ratio of weight applied to a pair of legs (LWR) when the cow was standing was calculated using a special weigh scale, and the cows were gait scored using a 1 to 5 NRS. Hoof lesions were scored and the cows placed into 1 of 4 mutually exclusive categories of hoof lesion: a) no lesions, b) moderate or severe hemorrhages, c) digital dermatitis, and d) sole ulcers. Regression analysis and receiver operating characteristic (ROC) curves were used to analyze the relation between hoof lesions and LWR. A clear relationship was found between NRS and LWR for the cows with sole ulcers ($R^2 = 0.79$). The LWR could differentiate cows with sole ulcers from sound cows with no hoof lesions [area under the curve (AUC) = 0.87] and lame cows from nonlame cows with lameness thresholds NRS >3 (AUC = 0.71) and NRS ≥3.5 (AUC = 0.88). There was no relationship between LWR and NRS for cows with digital dermatitis. Measurement of how cows distribute their weight when standing holds promise as a method of automated detection of lameness.
Key words: dairy cattle, lameness, automated detection, hoof lesion

INTRODUCTION

Although lameness is one of the most costly health and welfare problems affecting dairy cows, surveys show that dairy producers consistently underestimate the number of lame cows on their farms (Whay et al., 2003; Espejo et al., 2006), which emphasizes the need for better methods of detecting lameness on farms. The increasing size of dairy farms results in reduced time available for producers to observe their cows, so automated methods of detecting lameness are being developed. Measure of cow visits to automated milking systems (Borderas et al., 2008) and of ground reaction force when cows are walking (Rajkondawar et al., 2006) can help detect lameness, but these measures suffer from low specificity or sensitivity (Bicalho et al., 2007).

Lame cows reduce the weight they place on the lame leg when standing, and measures of how cows distribute their weight between their legs have been used to identify lame cows (Pastell et al., 2006; Rushen et al., 2007). Repeated measures of weight distribution of individual cows accumulated over a long period of time showed high specificity and sensitivity in identifying lame cows being milked in an automated milking system (Pastell and Kujala, 2007). But, there have been only small scale studies of the ability of such measures to distinguish between lame and healthy cows using measures taken during a short period of time (Rushen et al., 2007), as might occur when new animals enter the herd or when lameness prevalence is being estimated in an animal welfare audit, for instance. Further application of this method of lameness detection requires that the method be tested on a wider number of farms.

The objective was to examine the ability of measures of weight distribution, taken over a short period of time, to identify lame cows and cows suffering from a variety of hoof lesions

MATERIALS AND METHODS

Animals and Housing

Lactating Holstein cows were housed in groups of 12 to 48 cows with at least 1 sand-bedded freestall (2.4 m long × 1.18 m wide × 0.40 m deep) per cow at the University of British Columbia's Dairy Education and Research Centre (Agassiz, Canada). Cows were supplied with fresh TMR twice daily at 0700 and 1600 h formulated to meet requirements for lactating dairy

Received May 15, 2009.
Accepted November 23, 2009.
[1]Corresponding author: matti.pastell@helsinki.fi

cows (NRC, 2001). Water was freely available from self-filling troughs. Lactating cows were milked twice daily at approximately 0800 and 1700 h. From the herd of 220 lactating cows, 68 lactating cows (mean ± SD: parity = 2.6 ± 1.7, range: 1 to 9; BW = 672 ± 82 kg; DIM = 181 ± 65; daily milk production = 35.1 ± 7.1 kg) were randomly selected from an unsorted list of cow numbers supplied by the barn manager.

Weighing Platform

The cows stood on a platform (Neveux et al., 2006; Chapinal et al., 2009a) situated at the end of a passageway that was used for gait scoring (described below) to measure how cows distributed their weight between their legs. The cows stood individually on the platform for 3 min during each measurement for a total of 1 to 4 measurements. All measurements were taken within a period of 3 to 7 d. Cows were familiarized with the platform by making them stand on it 4 times/d for at least 4 d before they were recorded. The platform contained 4 independent recording units (each 56 × 91 cm) fitted in a 1.9- × 1.3-m enclosure. The weight placed on each leg was recorded at a rate of 6 Hz. The platform was calibrated periodically during the experiments using dead-weight calibration with standard weights.

Gait Score

Immediately after the morning milking, the cows were videotaped while walking down the 13-m long by 1.3-m wide nongrooved concrete passageway that led to the weighing platform. A handler walked immediately behind the cows encouraging them when necessary to walk in a consistent manner. Cows were habituated to the procedure by being repeatedly walked down the passageway for at least 4 d (4 passages/d) before gait scoring. Each cow was videotaped during each passage at normal speed from her right side with a color digital camera (30 frames/s, Sony DCRSR100 HDD Handycam Camcorder, Sony Corp., Park Ridge, NJ) placed 8 m from the cow to allow recording of at least 4 complete strides during each passage. These video recordings were used to gait score the cows. A second video camera (Panasonic CCTV WV-BP310, Matsushita Electric, Mississauga, Ontario, Canada) connected to a time-lapse videocassette recorder (Panasonic Time-Lapse VCR, AG-6740, at normal speed in 2-h mode, 25 frames/s) was mounted 2.7 m above the floor and pointed toward the posterior of the cow, which enabled scoring of the abduction/adduction of the rear legs. An experienced observer watched the videos and evaluated 7 specific gait attributes (abduction/adduction of the rear legs, back arch, head bob, tracking-up, joint flexion, asymmetric gait, and reluctance to bear weight) as described in Flower and Weary (2006) and Chapinal et al. (2009b). Individual overall gait score was assessed by using a 1 to 5 numerical rating score system (**NRS**; where 1 = perfect gait and 5 = severely lame) based on the 7 specific gait attributes. If a cow exceeded the requirements of a particular score, a half-integer score was allocated. The gait scoring was done without knowledge of the hoof quality scores and vice versa.

Clinical Examination of the Hooves

Between 1 and 6 d after completion of the measurements of weight distribution and gait scoring, the soles of the hooves were pared minimally by a trained hoof trimmer to expose a clean surface and examined for the presence of various hoof lesions. An experienced observer examined the front and rear hooves of the cows and recorded the presence and severity of hemorrhages, sole ulcers, and digital dermatitis. Hemorrhages and ulcers were scored on a 1 to 8 scale as described by Leach et al. (1998; 1 = diffuse red or yellow; 2 = stronger red; 3 = deep dense red; 4 = port coloration; 5 = red, raw, 6 = ulcer, corium exposed; 7 = severe ulcer, major loss of horn; and 8 = infected ulcer). Hemorrhages were scored wherever they occurred on the base of the claw and were not limited to the sole. Digital dermatitis was scored on a 1 to 5 scale as described by Manske et al. (2002; 1 = reddened area with erect pili; 2 = moist, discharge, reddened area with intact epidermis; 3 = exudative area, exposed corium, no signs of healing; 4 = exposed corium, but in process of healing, dried up lesion; and 5 = dark brown scab, completely almost/completely healed lesion).

Data and Statistical Analysis

Sometimes the cows did not stand directly on the balances, which resulted in errors in the data. The erroneous data points were located as changes in the measured total weight of the cows and were removed using an automatic algorithm described in Pastell et al. (2008). If less than 90 s of the original weight measurement remained after the error correction, then the measurement was not used in further analysis. After the error correction, data from 61 cows remained for statistical analysis.

After removing erroneous values from the data, the average weight placed on each leg, the standard deviation (over time) of the weight placed on each leg, and the number of leg lifts for each leg were calculated for each measurement. A leg lift was calculated when the weight placed on a leg decreased to <20 kg and increased again over the same limit (Pastell et al., 2006).

The mean of standard deviations of weight applied to 4 legs and the mean number of leg lifts during each measurement were calculated over the 4 legs. Mean values over the measurements were calculated for each cow.

To describe the relative amount of weight placed on all legs, a single variable based on the ratio of weight (lighter leg/heavier leg) placed on the 2 rear legs (**HLR**) and the ratio of weight placed on the 2 front legs (**FLR**) was calculated. The smaller of FLR and HLR was taken as the leg weight ratio (**LWR**; Pastell et al., 2006), which was used to measure the maximum weight asymmetry for each cow. A low value for LWR indicated a large asymmetry between a pair of legs. The raw measurement data was processed using Matlab R2008a (The Mathworks, Natick, MA).

Gait scores for each cow (1 passage/d per cow) were averaged to provide a single value for NRS for each cow. Cows had a hoof lesion if at least 1 digit was affected. Hoof lesions were categorized into 4 mutually exclusive categories for the analysis: a) cows with no lesions, b) cows with moderate or severe hemorrhages only (lesion score 3 to 5), c) cows with digital dermatitis (that could also have hemorrhages,), and d) cows with sole ulcers (lesion score ≥6; that could also have hemorrhages). No cows had both sole ulcers and digital dermatitis. Cows with other kinds of lesions (e.g., interdigital hyperplasia) but without having hemorrhages, sole ulcers, or digital dermatitis were not included in the analysis of the relation of lesions to LWR (n = 6).

Correlations were calculated between LWR, the mean of standard deviations of the weight on the 4 legs during each measurement, the mean number of leg lifts during each measurement, and NRS. A multiple linear regression model was used between LWR (response variable) and NRS, standard deviation of weight, and the number of leg lifts to identify linear multivariate relations in the data.

The overall differences in LWR between cows within different categories of hoof lesions were tested with a nonparametric Wilcoxon rank sum test with a Holm correction for multiple comparisons. Separate simple linear regression models between LWR (response variable) and NRS (predictor variable) were tested for each category of hoof lesions to determine if the relation between variables differed between lesion categories. The normality and homogeneity assumptions of the regression models were checked with a normal probability plot of studentized (jackknifed) residuals and scatter plot of studentized residuals against fitted values.

A Spearman correlation between the lesser of FLR and HLR and the greater of FLR and HLR for each cow was calculated to examine if there was a linear relation between the weight asymmetry of the rear and front pairs of legs; that is, if an asymmetry in weight distribution between one pair of legs was reflected in an asymmetry in weight distribution between the other pair of legs.

Receiver operating characteristic (**ROC**) curves were used to evaluate the suitability of LWR for separating lame cows from sound cows, using 2 different threshold values for lameness. The ROC was used for separating LWR of cows with sole ulcers or hemorrhages from cows with no lesions. The ROC analysis was used to evaluate the accuracy of a model or test in separating positive from negative cases. The ROC curves captured the trade-off between sensitivity and specificity over the entire range of a model with continuous values, and the results were independent of the prevalence of positive cases in the study population (Lasko et al., 2005). The discrimination accuracy of a test was described with an area under the curve (**AUC**). An AUC of 1 represented perfect discrimination and an AUC of 0.5 represented no discrimination (Hanley and McNeil, 1982; Lasko et al., 2005). The ROC curve and the corresponding AUC were approximated using a nonparametric method because it imposed no structural assumptions on the data (Lasko et al., 2005), which was equivalent to the 2-sample Wilcoxon rank sum statistic.

Because of the rather small sample size, bootstraps were used to estimate the bias of AUC for all ROC curves. The bootstrap procedure was used to estimate if the results from the smaller data set were applicable to the larger population. It is a statistical technique that can be used to estimate the bias and variability of any population parameter θ using extensive repeated calculations (Efron, 1979; Davison and Hinkley, 1997). The nonparametric (ordinary) bootstrap was used, which does not have any other structural assumptions other than that samples were random and independently distributed. The procedure involved taking m random samples from the original data x (LWR) with replacement creating a new bootstrap sample x^* (LWR*). The bootstrap sampling was repeated n times and the parameter of interest θ (AUC) was calculated for each sample x^*. The bootstrap estimate θ^* (AUC*) was obtained as the mean of all bootstrap samples. A small bias between the original parameter and θ and the bootstrapped parameter θ^* gave evidence that θ was a good estimate for the whole population (Efron, 1979; Venables and Ripley, 2002). The bootstrap was used with 10,000 iterations to estimate AUC*, which in turn was used to calculate the bias between AUC and AUC*. The Venables and Ripley (2002) procedure was followed in the computational implementation.

All statistical analyses were conducted using R 2.71 (R Development Core Team, 2008), the verification package (NCAR, 2008) was used for the ROC analysis, the boot package (Davison and Hinkley, 1997; Canty

Table 1. Distribution of numerical rating scores[1] (NRS, where 1 = perfect gait and 5 = severely lame) for cows with no hoof lesions, cows with digital dermatitis, cows with hemorrhages, and cows with sole ulcers

NRS	Cows, n
2	11
2.5	9
3	23
3.5	7
4	5

[1]The numbers are rounded to the nearest half-integer.

Table 2. Distribution of different lesions for cows with no hoof lesions, cows with digital dermatitis, cows with hemorrhages, and cows with sole ulcers

Lesion	Cows, n
No lesions	16
Hemorrhages	15
Digital dermatitis[1]	12
Sole ulcers[1]	12
Other lesions	6

[1]Cows could also have hemorrhages.

and Ripley, 2008) for bootstraps, and the MASS package (Venables and Ripley, 2002) for regression diagnostics.

RESULTS

The distribution of NRS and different lesions diagnosed in the experiment are in Tables 1 and 2. There was a positive correlation (r = 0.66, $P < 0.001$) between the weight asymmetry of the 2 pairs of legs. However, a large asymmetry in weight within 1 pair of legs was not always matched by a large asymmetry in weight within the other pair of legs (Figure 1).

There was a negative correlation between NRS and LWR (r = −0.63, $P < 0.001$) such that cows with high NRS had a greater asymmetry in weight within 1 pair of legs. Numerical rating score had an effect on LWR in the multiple linear regression model ($P < 0.001$), but the relation between LWR and NRS varied between the different categories of hoof lesions (Figure 2). There was a linear relation between LWR and NRS for cows with sole ulcers ($R^2 = 0.79$, $P < 0.001$), a tendency of a relation for cows with hemorrhages only ($R^2 = 0.22$, $P = 0.08$), and no relation for cows with dermatitis ($P = 0.96$) or cows with no lesions ($P = 0.24$).

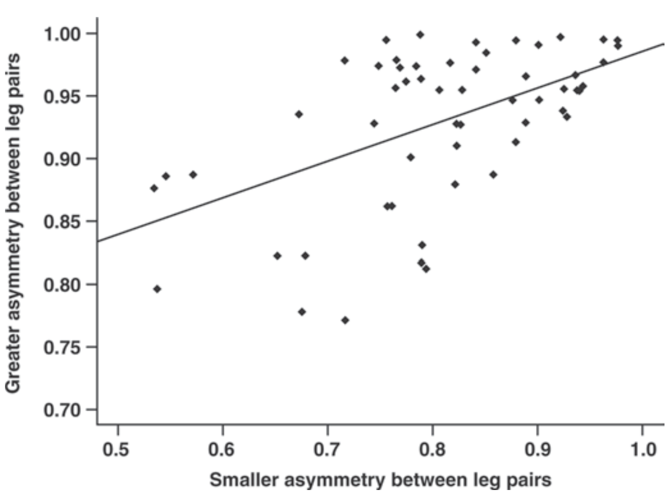

Figure 1. Relationship between the weight asymmetries of the leg pairs. Each point represents a single cow (n = 61).

The mean of standard deviations of weight applied to each leg and the number of leg lifts during the measurement were both uncorrelated with LWR and NRS and not significant in the regression model ($P > 0.05$). Therefore, the focus was on analyzing the relation between LWR and NRS in more detail.

The ROC curves were used to test how well LWR discriminated between lame and sound cows (Figure 3). Two threshold NRS values (>3 and ≥3.5) were used for lameness. The threshold value had a significant effect in discriminating lame cows from sound ones using LWR (Figure 3). The AUC for the groups NRS >3 and NRS ≥3.5 were 0.71 ($P < 0.001$) and 0.88 ($P < 0.001$), respectively.

The LWR was successful at discriminating between cows with different categories of hoof lesions. The LWR of cows with sole ulcers differed from those with no lesions or with dermatitis ($P < 0.05$), but not from those with hemorrhages only (Figure 4). The ROC curves showed that LWR is very good (AUC = 0.87, $P < 0.001$) at discriminating sound cows; that is, with no hoof lesions and NRS ≤3, from cows with sole ulcers and hemorrhages (Figure 5). There was a reasonable ability to discriminate between the cows with hemorrhages and sound cows with no lesions (AUC = 0.71, $P < 0.05$). The bootstrapped bias between AUC and AUC* was <0.01 for all ROC curves (Figures 3 and 5), indicating that AUC were good estimates of the true AUC for the respective populations.

DISCUSSION

The LWR is a measure of the difference or degree of asymmetry in weight applied to a contralateral pair of legs when the cow is standing (Pastell and Kujala, 2007). The results show that this variable can be used to discriminate lame cows from sound cows, and cows with no hoof lesions from cows with relatively severe sole ulcers, and to a lesser extent, cows with severe

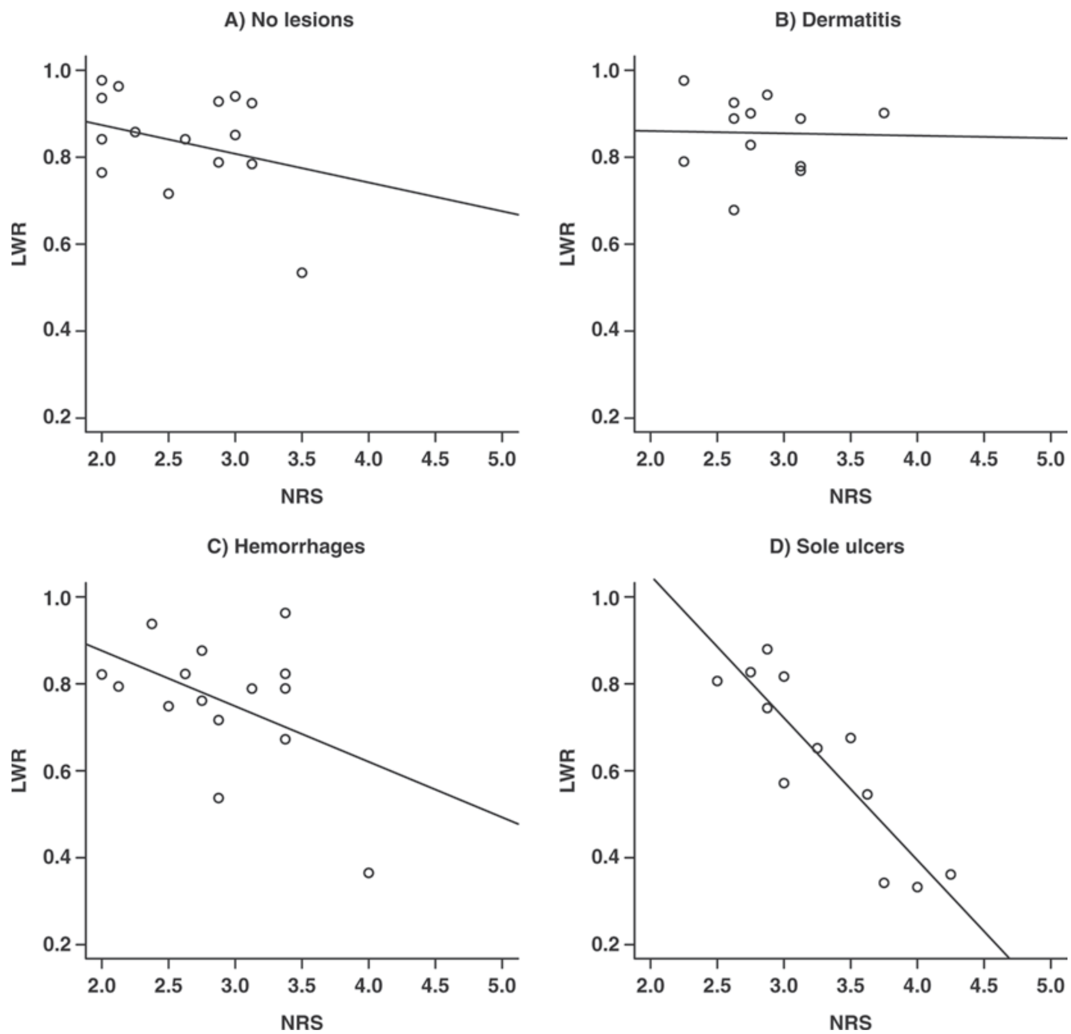

Figure 2. Relation between the ratio of weight applied to a pair of legs (leg weight ratio, LWR) and numerical rating score (NRS) for A) cows with no hoof lesions (n = 16), B) cows with digital dermatitis (n = 12), C) cows with hemorrhages (n = 15), and D) cows with sole ulcers (n = 12).

hemorrhages. This holds promise as a method of identifying lame cows being milked in an automated milking system.

Our results support previous findings showing the effect of lameness and hoof lesions on this measure or other measures of how cows distribute their weight between their legs (Pastell and Kujala, 2007; Rushen et al., 2007). The LWR can help to identify lame cows either when cows are followed over a long period of time (Pastell et al., 2006; Pastell and Kujala, 2007; Pastell and Madsen, 2008) or when data are collected over only a short period as in this study. The accuracy of LWR to detect lame cows was higher when an NRS score of 3.5 was used compared with an NRS score of 3.0 as the threshold for identifying a cow as being lame. Sound cows had a large variance in their LWR, which made the detection of mild lameness cases challenging. Previously it was shown that accumulating several measurements from the same cow improved the lameness detection rate (Pastell and Kujala, 2007) including that for less severe cases. Furthermore, individual statistical models for each cow yielded better sensitivity than general models that were applied to all cows (Pastell and Madsen, 2008).

Interestingly, some cows were not detected as lame with LWR although they were visibly lame according to their NRS. It is possible that a cow may suffer pain when walking that is not as obvious when the cow is standing still. This may be because of several undiagnosed causes behind functional lameness, such as thickened joint capsules, nerve or ligament injury, and muscle problems that do not affect standing. Hoof lesions on multiple legs may complicate measures of LWR. In addition, some sole ulcers seemed to cause

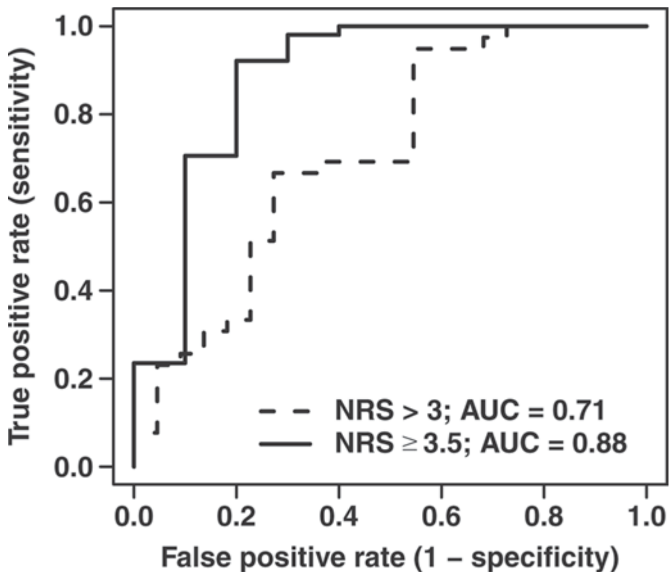

Figure 3. Receiver operating characteristic (ROC) curves between the true positive rate and the false positive rate when the ratio of weight applied to a pair of legs (leg weight ratio, LWR) was used to discriminate between sound cows and lame cows using 2 different thresholds for numerical rating score (NRS) for a cow categorized as lame (n = 22 for NRS >3 and n = 10 for NRS ≥3.5); AUC = area under the curve.

changes in LWR, but did not result in visible lameness as shown by the NRS (Figures 2d and 5). Thus, the LWR may help identify sole ulcers in cows that are not obviously lame. A threshold of 3.5 had a higher accuracy but smaller sensitivity in discriminating cows with sole ulcers from cows with no hoof lesions (Chapinal et al., 2009b).

Interestingly, LWR was less successful at identifying cows with only hemorrhages and was not able to discriminate between cows with no hoof lesions and cows with digital dermatitis. This supports findings that the NRS was less successful in identifying cows with these types of hoof lesion (Flower and Weary, 2006; Flower et al., 2007; Chapinal et al., 2009b), suggesting that these particular hoof lesions may cause less pain than sole ulcers. But the cases of digital dermatitis were relatively mild, and we must be cautious in extending the findings to more severe cases. Furthermore, hemorrhages were included wherever they occurred on the base of the claw, and the location of the hemorrhage may affect the degree of pain associated with it. The intermediate LWR of cows with hemorrhages suggest that some of the hemorrhages were painful and others not. It was suggested that hemorrhages in different locations are caused by different factors (Leach et al., 1998; Manske et al., 2002). It is possible that some of the hemorrhages were ulcers in the process of developing but that were not yet visible on the hoof (Bergsten, 2004).

There was no correlation between the presence of sole ulcers or lameness and the variability of the weight placed on each leg over time (as measured by the mean of the standard deviations of weight on the 4 legs and number of leg lifts during each measurement). This contradicts our previous findings (Pastell and Kujala, 2007; Rushen et al., 2007). However, in those previous studies, the weight variability in the same animals before and after pain medication (Rushen et al., 2007) was compared, or repeated measurements were made of individual cows in a milking robot, which can influence their behavior (Pastell and Kujala, 2007), suggesting that the variability over time in weight applied to the legs could be a good measure for detecting when individual cows were becoming lame, but may not be suitable for discriminating between lame and sound cows using data collected over a short period of time.

Our results show a correlation between weight asymmetry of the hind pair and the front pair of legs. This supported some of our earlier findings that the change in the weight distribution due to lameness in the rear legs caused an opposite weight shift in the front legs to hold the animal in balance (Pastell et al., 2006). Yet, in other studies, there was no effect (Neveux et al., 2006). Several situational factors might influence how cows distribute their weight between their legs (Chapinal et al., 2009a) and these must be taken into account when using such data to detect lame cows.

CONCLUSIONS

The asymmetry of weight distribution (LWR) within a pair of contralateral legs was a sensitive measure for

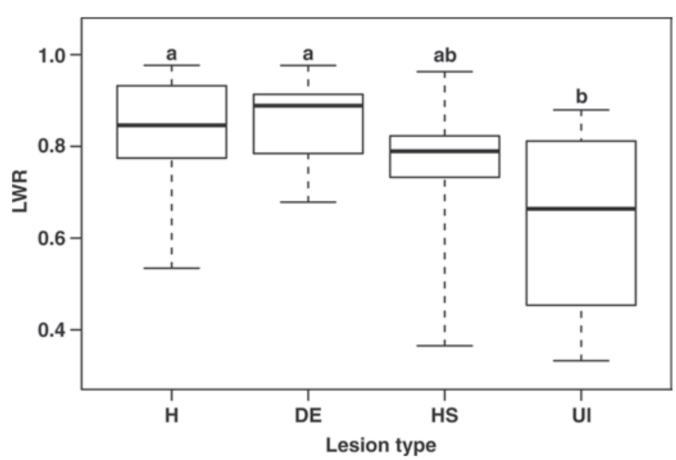

Figure 4. Box plots showing the 25th and 75th percentile (box), median (center line), and extreme values (whiskers) for the ratio of weight applied to a pair of legs (leg weight ratio, LWR) of cows having no lesions (H, n = 16), cows with digital dermatitis (DE, n = 12), cows with hemorrhages only (HS, n = 15), and cows with sole ulcers (UI, n = 12). [a,b]Boxes lacking a common letter differ ($P < 0.05$).

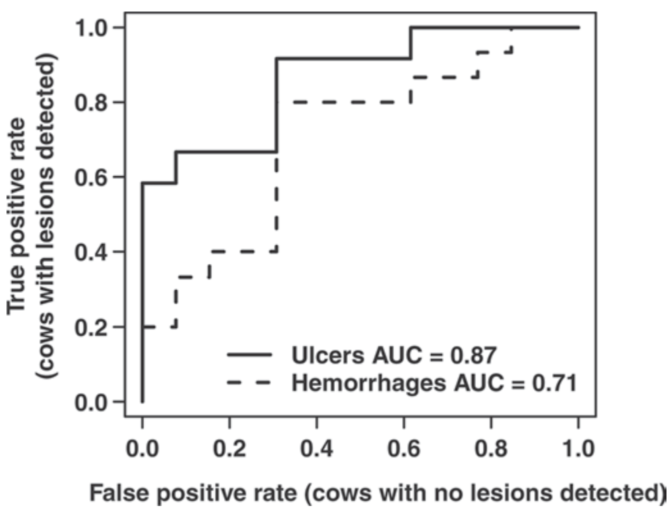

Figure 5. Receiver operating characteristic (ROC) curves between the true positive rate and the false positive rate when the ratio of weight applied to a pair of legs (leg weight ratio, LWR) was used to discriminate between cows with no lesions (n = 16) and cows with ulcers (n = 12) and cows with hemorrhages (n = 15); AUC = area under the curve.

detecting visibly lame cows and cows suffering from relatively severe sole ulcers. Mild lameness caused by dermatitis or hemorrhages was not easily detected using data collected over a short period of time and may require repeated measures on individual cows to detect changes that occur over time.

ACKNOWLEDGMENTS

We thank Gosia Zdanowicz, Mairi Robertson, Nuria Chapinal, and the faculty, staff and students at The University of British Columbia's Dairy Education and Research Centre Agriculture and Agri-Food Canada for their help in running the experiments. The research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Animal Compassion Foundation (now Global Animal Partnership Inc.), and Agriculture and Agri-Food Canada.

REFERENCES

Bergsten, C. 2004. Causes, risk factors, and prevention of laminitis and related claw lesions. Acta Vet. Scand. 44(Suppl. 1):157–166.

Bicalho, R. C., S. H. Cheong, G. Cramer, and C. L. Guard. 2007. Association between a visual and an automated locomotion score in lactating Holstein cows. J. Dairy Sci. 90:3294–3300.

Borderas, F., A. Fournier, J. Rushen, and A. M. de Passillé. 2008. Effect of lameness on dairy cow's visits to automatic milking systems (AMS). Can. J. Anim. Sci. 88:1–8.

Canty, A., and B. Ripley. 2008. boot: Bootstrap R (S-Plus) Functions. R package version 1.2–36. http://cran.r-project.org/package=boot Accessed May 14, 2009.

Chapinal, N., A. M. de Passillé, and J. Rushen. 2009a. Weight distribution and gait in dairy cattle are affected by milking and late pregnancy. J. Dairy Sci. 92:581–588.

Chapinal, N., A. M. de Passillé, D. M. Weary, M. A. G. von Keyserlingk, and J. Rushen. 2009b. Using gait score, walking speed, and lying behavior to detect hoof lesions in dairy cows. J. Dairy Sci. 92:4365–4374.

Davison, A. C., and D. V. Hinkley. 1997. Bootstrap Methods and Their Applications. Cambridge University Press, Cambridge, UK.

Efron, B. 1979. Bootstrap methods: Another look at the jackknife. Ann. Stat. 7:1–26.

Espejo, L. A., M. I. Endres, and J. A. Salfer. 2006. Prevalence of lameness in high-producing Holstein cows housed in freestall barns in Minnesota. J. Dairy Sci. 89:3052–3058.

Flower, F. C., A. M. de Passillé, D. M. Weary, D. J. Sanderson, and J. Rushen. 2007. Softer, higher-friction flooring improves gait of cows with and without sole ulcers. J. Dairy Sci. 90:1235–1242.

Flower, F. C., and D. M. Weary. 2006. Effect of hoof pathologies on subjective assessments of dairy cow gait. J. Dairy Sci. 89:139–146.

Hanley, J., and B. McNeil. 1982. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143:29–36.

Lasko, T. A., J. G. Bhagwat, K. H. Zou, and L. Ohno-Machado. 2005. The use of receiver operating characteristic curves in biomedical informatics. J. Biomed. Inform. 38:404–415.

Leach, K. A., D. N. Logue, J. M. Randall, and S. A. Kempson. 1998. Claw lesions in dairy cattle: Methods for assessment of sole and white line lesions. Vet. J. 155:91–102.

Manske, T., J. Hultgren, and C. Bergsten. 2002. Prevalence and interrelationships of hoof lesions and lameness in Swedish dairy cows. Prev. Vet. Med. 54:247–263.

NCAR. 2008. Verification: Forecast verification utilities. R package version 1.29. http://cran.r-project.org/package=verification Accessed May 14, 2009.

Neveux, S., D. M. Weary, J. Rushen, M. A. von Keyserlingk, and A. M. de Passillé. 2006. Hoof discomfort changes how dairy cattle distribute their body weight. J. Dairy Sci. 89:2503–2509.

NRC. 2001. Nutrient Requirement of Dairy Cattle. 7th rev. ed. National Academy Press, Washington, DC.

Pastell, M., M. Hautala, V. Poikalainen, J. Praks, I. Veermäe, M. Kujala, and J. Ahokas. 2008. Automatic observation of cow leg health using load sensors. Comput. Electron. Agric. 62:48–53.

Pastell, M., and H. Madsen. 2008. Application of CUSUM charts to detect lameness in a milking robot. Expert Syst. Appl. 35:2032–2040.

Pastell, M., H. Takko, H. Gröhn, M. Hautala, V. Poikalainen, J. Praks, I. Veermäe, M. Kujala, and J. Ahokas. 2006. Assessing cows' welfare: Weighing the cow in a milking robot. Biosystems Eng. 93:81–87.

Pastell, M. E., and M. Kujala. 2007. A probabilistic neural network model for lameness detection. J. Dairy Sci. 90:2283–2292.

R Development Core Team. 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org Accessed May 14, 2009.

Rajkondawar, P. G., M. Liu, R. M. Dyer, N. K. Neerchal, U. Tasch, A. M. Lefcourt, B. Erez, and M. A. Varner. 2006. Comparison of models to identify lame cows based on gait and lesion scores, and limb movement variables. J. Dairy Sci. 89:4267–4275.

Rushen, J., E. Pombourcq, and A. M. de Passillé. 2007. Validation of two measures of lameness in dairy cows. Appl. Anim. Behav. Sci. 106:173–177.

Venables, W. N., and B. D. Ripley. 2002. Modern Applied Statistics with S. 4th ed. Springer, New York, NY.

Whay, H. R., D. C. Main, L. E. Green, and A. J. Webster. 2003. Assessment of the welfare of dairy cattle using animal-based measurements: Direct observations and investigation of farm records. Vet. Rec. 153:197–202.