Lameness in dairy cattle: A debilitating disease or a disease of debilitated cattle? A cross-sectional study of lameness prevalence and thickness of the digital cushion

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ABSTRACT

Lameness is the most significant challenge for the dairy industry to overcome, given its obvious disruption of animal welfare and severe economic losses. Sole ulcers and white line abscesses are ubiquitous chronic diseases with the highest associated economic losses among all foot lesions. Their underlying causes are still not fully understood. An observational cross-sectional study was carried out to investigate the association between claw horn lesions and the thickness of the digital cushion. The thickness of the digital cushion was evaluated by ultrasonographic examination of the sole at the typical ulcer site. A total of 501 lactating Holstein dairy cows were enrolled in the study. The prevalence of sole ulcers was 4.2 and 27.8% for parity 1 and parity >1, respectively. The prevalence of white line disease was 1.0 and 6.5% for parity 1 and >1, respectively. The prevalence of lameness (visual locomotion score ≥ 3) was 19.8 and 48.2% for parity 1 and >1, respectively. The prevalence of sole ulcers and white line diseases was significantly associated with thickness of the digital cushion; cows in the upper quartile of digital cushion thickness had an adjusted prevalence of lameness 15 percentage points lower than the lower quartile. Body condition scores were positively associated with digital cushion thickness. The mean gray value of the sonographic image of the digital cushion had a negative linear association with digital cushion thickness ($\mathbb{R}^2 = 0.14$), indicating that the composition of the digital cushion may have changed with its thickness. Furthermore, digital cushion thickness decreased steadily from the first month of lactation and reached a nadir 120 d after parturition. These results support the concept that sole ulcers and white line abscesses are related to contusions within the claw horn capsule and such contusions are a consequence of the lesser capacity of the digital cushion to dampen the pressure exerted by the third phalanx on the soft tissue beneath.

Key words: dairy cow, lameness, digital cushion, body condition score

INTRODUCTION

A growing concern of the dairy industry is to increase dairy cattle wellbeing in anticipation of a demand from consumers of welfare-certified dairy products. Lameness is one of the most important welfare issues of high-producing dairy cows in North America (Vermunt, 2007). It is a debilitating condition that challenges the sustainability of production systems used in North America because of the pain and subsequent animal welfare consequences (Vermunt, 2007) and the significant economic losses (Warnick et al., 2001). A study conducted in England concluded that lameness was the second most costly disease in the dairy industry after mastitis (Kossaibati and Esslemont, 1997).

Lameness results in earlier culling of animals as well as lower carcass weight, conformation class, and fat cover class and hence a lower carcass economic value (Booth et al., 2004; Bicalho et al., 2007b; Fjeldaas et al., 2007). It has also been reported that prevention or early identification and treatment of the problem can improve the value of the carcass and reduce culling rates (Fjeldaas et al., 2007). Several studies have also shown that lameness has a negative effect on the fertility of dairy cows (Sprecher et al., 1997; Hernandez et al., 2001; Garbarino et al., 2004). More recently, it has been reported that cows detected with clinical lameness in the first 70 DIM were 25% less likely to become pregnant compared with nonlame cows (Bicalho et al., 2007b). The prevention of lameness is the most important step to reduce the negative welfare implications for cows and costs for the farmers (Mill and Ward, 1994); hence, the importance of creating a system that accurately predicts the occurrence of lameness allowing farmers to target high-risk animals with preventive strategies.

Despite the undeniable relevance of lameness (resulting from claw horn disorders) very little is known about the etiology and pathophysiology of the nonin-

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fectious diseases associated with lameness. Although severe cases of laminitis (inflammation of the laminar tissue of the digit) caused by abnormally high intake of readily available carbohydrates have been described in the literature (Bazeley and Pinsent, 1984), the link between subclinical laminitis and claw lesions has been challenged lately (Logue et al., 2004). To make matters worse, research knowledge on the pathogenesis of equine laminitis was uncritically generalized to the field of bovine lameness without taking into account the profound anatomical and physiological differences between the two species. Thus far, there is limited evidence that claw horn lesions in cattle are caused by subclinical laminitis (Lischer et al., 2002; Logue et al., 2004; Thoefner et al., 2004). Lately, the hypothesis that claw lesions are a consequence of contusions within the claw horn capsule has been suggested (Tarlton et al., 2002; Räber et al., 2004). Räber et al. (2004) reported that it is widely accepted by researchers in the Northern Hemisphere that most bovine claw lesions (and thus lameness) originate from contused tissue within the claw horn capsule. Although it has been reported that sole ulcers and white line lesions are caused by subclinical laminitis (Thoefner et al., 2004), others clearly state that the evidence to support this is limited (Logue et al., 2004). The suspensory apparatus in cattle is less well developed than in the horse and the digital cushion must support a considerably greater proportion of the body weight (Räber et al., 2004). The digital cushion is a complex structure (composed mostly of adipose tissue) located underneath the distal phalanx and plays an important function of dampening compression of the corium tissue beneath the cushion. The biomechanical importance of the digital cushion in alleviating compression under the tuberculum flexorum of the distal phalanx is well known (Logue et al., 2004; Räber et al., 2004, 2006).

A recent study has shown that cows with low BCS around parturition had 3 to 9 times higher odds of developing lameness compared with cows with higher BCS (Hoedemaker et al., 2008). Additionally, lameness incidence increases with age and older cows tend to have increased levels of hoof damage, lower BCS, and lower overall digital cushion thickness (Räber et al., 2004). Hence, low BCS may be associated with decreased digital cushion thickness; thinner digital cushions would have lower capacity to dampen compression of the corium by the third phalanx. No published peer-reviewed research has attempted to associate BCS and thickness of digital cushion. Thickness of the digital cushion can easily be assessed by sonographic examination of the sole (van Amstel et al., 2004).

The objectives of the present study were to assess the association of digital cushion thickness, measured by sonographic examination of the sole at the ulcer site, and the risk of claw horn disruption lesions. It was also an objective of the study to assess the dynamics of digital cushion thickness (**DCT**) by stage of lactation and BCS. It was hypothesized that DCT would be negatively associated with the risk of digital lesions and positively associated with BCS.

MATERIALS AND METHODS

Case Definition

Lameness was defined by presence of a painful sole ulcer or white line disease and by visual locomotion scores (**VLS**; Bicalho et al., 2007a). The system used was a 5-point scale: 1 = normal, 2 = presence of a slightly asymmetric gait, 3 = cow clearly favors 1 or more limbs (moderately lame), 4 = severely lame, and 5 = extremely lame (non-weight-bearing lame). Pain was defined by reaction to gentle pressure applied by hand to the lesions. In the instance of a clearly painful lesion, such as a sole ulcer with substantial exposure of corium tissue, the cow was spared from having pressure applied to the lesion. Scoring was completed by 1 of 3 researchers (2 veterinarians and a senior veterinary student) who were trained or had extensive experience with VLS.

Farm and Management

Data were collected from a dairy farm located near Ithaca, New York, from July 15 to September 10, 2008. This farm was selected because of its long history of a working relationship with the Ambulatory and Production Medicine Clinic at Cornell University. The farm milked 2,800 Holstein cows 3 times daily in a double 52-stall parallel milking parlor. The cows were housed in free-stall barns with concrete stalls covered with mattresses and bedded with waste paper pulp. The feed alleys had grooved-concrete flooring and were cleaned by automatic scrapers. All walkways to and from the milking barn and the holding pen were covered with rubber. Footbaths were located in the exit lanes of the milking parlor. The footbath consisted of a 5% formalin solution applied at least 4 times weekly according to labor schedule and availability. Each individual cow was scheduled to receive routine hoof trimming twice vearly; a protocol was created in DairyComp 305 (Valley Agricultural Software, Tulare, CA) that prompted lactating cows for routine trimming when they were past 150 d since the last time they received a routine hoof trimming. Furthermore, all cows received a regular hoof trimming at dry off. Lame cows were identified by visual detection of asymmetric gait (lameness) of





Figure 1. Diagram of the sole region of the bovine digit enumerating the several different anatomical areas of the sole. The ultrasonographic examination was performed in the medial aspect of area 4 (typical ulcer site). Figure courtesy of Zinpro Corporation (Eden Prairie, MN).

cows returning from the milking parlor; a systematic lameness scoring system was not used by the farm employees. Treatment of lame cows was also performed by trained farm employees.

All cows were offered a TMR consisting of approximately 55% forage (corn silage, haylage, and wheat straw) and 45% concentrate (corn meal, soybean meal, canola, cottonseed, and citrus pulp) on a DM basis. The diet was formulated to meet or exceed the nutrient requirements (NRC) for lactating Holstein cows weighing 650 kg and producing 45 kg of 3.5% FCM.

Data Collection and Study Design

A cross-sectional observational study design was used. The data were collected using a convenience sample of lactating dairy cows that were scheduled for routine or therapeutic hoof trimming. Hoof trimming was completed by farm employees or one of the research team members (2 veterinarians and a veterinary student). The cattle were restrained for hoof trimming with a standing hoof trimming chute HSeries (Comfort Hoof Care, Baraboo, WI). Before cows entered the trimming chute, the following data were collected by a member of the research team: BCS, which ranged from 1 to 5 with a quarter point system as described by Edmonson et al. (1989); cow height measurement, assessed as the distance in centimeters from the floor to the dorsal aspect of the caudal sacral joint; and locomotion score as described previously. Agreement between observers was

not assessed for any of the subjective scores used because only one observer scored cows at any given time. Factors such as parity number, stage of lactation, and parturition date were obtained from the farms database in Dairy Comp 305 (Valley Agricultural Software).

Immediately after the cows were hoof trimmed, they underwent digital sonographic B-mode examination with an Aquila Vet ultrasound machine (Esaote Europe BV, Maastricht, the Netherlands) equipped with a curved array dual-frequency probe set at 7.5 MHz. The examination was always completed at the typical sole ulcer site (Figure 1) assessing the distance from the inner margin of the sole (Figure 2; identified as a thin echogenic line in Figure 3) to the distal edge of the tuberculum flexorum of the third phalanx (identified as a thick echogenic line; Figure 3). The anatomical area of the digital cushion targeted for ultrasonography was the middle pad (Räber et al., 2004). Before the beginning of the study, the ultrasound technique was evaluated in a pilot study (using 20 digits from cadaver feet) that assessed the association of ultrasound measurement and the actual measurement of the middle digital cushion pad after dissection of hooves. The ultrasound measurements of the middle digital cushion pad were not significantly different from the actual measurements of the dissected slaughterhouse specimens $[0.90 \pm 0.2]$ (SD) and 0.93 ± 0.2 cm, respectively). Ultrasonography of all 8 digits (411 cows) was completed only when at least 2 researchers were working together collecting data; when only one researcher was available to perform ultrasonography, only the 4 hind digits (501 cows) were examined to avoid disruption of the hoof trimming work.

Two ultrasound images per cow, one from the right medial front digit and another from the right lateral hind digit, were stored in the ultrasound machine memory card for image analysis; the 2 digits used were arbitrarily chosen. The ultrasound machine settings (i.e., depth, echo-amplification, persistence, pre- and postprocessing) were kept unchanged throughout the study. The echotexture of the ultrasound images was evaluated by calculating the mean gray value (MGV) using the free image software ImageJ (http://rsb.info. nih.gov/ij) developed by the National Institutes of Health. The MGV is used to describe the total brightness of the image. Mean gray values range from 0 to 255 and the higher the MGV the brighter the sonographic image. The area selected for image evaluation was the area between the inner margin of the sole and the distal edge of the tuberculum flexorum of the third phalanx.

Statistical Analysis

Descriptive statistics and univariate analysis were undertaken in SAS using the FREQ and UNIVARIATE



Figure 2. Sagittal section of the bovine digit illustrating the site of ultrasonographic measurement of digital cushion thickness. Figure courtesy of Zinpro Corporation (Eden Prairie, MN).

procedures (SAS Institute Inc., Cary, NC). To facilitate analysis and interpretation of results the following variables were categorized: stage of lactation (categorized in intervals of 30 DIM with the exception of stage of lactation 10, which represents cows with DIM >270), parity (parity 1 and parity >1), and mean digital cushion thickness (**MDCT**) of all 4 hind digits (categorized into 4 quartiles). To illustrate the linear association of MGV and DCT, a simple linear regression analysis was completed using MedCalc Version 9.5.0.0 (MedCalc Software, Mariakerke, Belgium).

A GLM was fitted to the data using the MIXED procedure (SAS Inst. Inc.). The outcome variable was MDCT (cm) of all hind digits, which was modeled as a Gaussian (normally distributed data) variable. The assumption that the residuals were normally distributed was satisfied by visually evaluating the distribution plot of the Studentized residuals. The following variables were offered to the model: lesion (present or absent), BCS, month of parturition, cow height, MGV, and stage of lactation. All possible 2-way interactions between the independent variables were added to the model. The variables were manually excluded from the model according to their respective *P*-values. The variables and their respective interaction terms were retained in the model when their *P*-values < 0.05. The GLM is described below:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{e},$$

where \mathbf{Y} = the average digital cushion thickness (centimeters) of all 4 hind digits, \mathbf{X} = the matrix of all independent variables, $\boldsymbol{\beta}$ = the vector of all fixed effect parameters, and e = random residual. To assess the association of digital cushion thickness and the risk of painful claw horn lesions (sole ulcers and white line disease) a logistic regression model was fitted in Stata (StataCorp LP, College Station, TX); the dependent variable of this model was claw horn lesion (1 = present and 0 = absent). To facilitate analysis and data interpretation, the variable MDCT (average DCT of all 4 hind digits) was categorized into 4 levels according to its distribution quartiles. The new categorical variable was named quartile digital cushion thickness (**QDCT**). The following variables were offered to the model as independent variables: QDCT, parity, stage of lactation, cow height, previous lactation length, MGV, and BCS.

All possible 2-way interactions between the independent variables were added to the model. The variables and their respective interaction terms in all models were retained in the model when their *P*-values were <0.05. The probability equation of the logistic regression was used to calculate the adjusted prevalence of lesions as described below:

$$P(lesion \mid \alpha, \beta) = \frac{e^{\sum \beta_i \mathbf{Z}_i}}{1 + e^{\sum \beta_i \mathbf{Z}_i}}$$

where $P(lesion | \alpha, \beta)$ is the adjusted probability that a cow had a lesion given a set of fixed factors Z_i (which were set to their respective averages) and the set of multiplicative slopes β_i .

To assess the model fit and the overall predictability of the final logistic regression model a receiver operating characteristic (**ROC**) curve analysis was performed by using the predicted probability estimates (from the logistic regression model) and the presence or absence of claw horn lesions (sole ulcers and white line disease) diagnosed at hoof trimming.

RESULTS

In total, 501 lactating dairy cows were examined and enrolled in the study. The median locomotion score of all cows enrolled in the study was 2 and the BCS was 3 (Table 1). The DCT of the right and left medial front digits was 0.91 and 0.89 cm, respectively. The DCT of the right and left lateral hind digits was 0.95 and 0.98 cm, respectively.

The prevalence of sole ulcers was 4.2 and 27.8% for parity 1 and parity >1, respectively (Table 2). The prevalence of white line disease was 1.0 and 6.5% for parity 1 and parity >1, respectively. The prevalence of lameness (VLS \geq 3) was 19.8 and 48.2% for parity 1 and parity >1, respectively. The MGV of the sonographic image of the digital cushion had a negative linear as-

Variable	Mean	Median	Range	SD	n
BCS	2.7	3.0	1.5 - 4.0	0.39	501
Locomotion score	2.3	2.0	1.0 - 5.0	0.8	501
Cow height, ¹ cm	144.9	145.0	132.0 - 159.0	4.4	501
Parity number	2.2	2.0	1.0 - 8.0	1.3	501
Digital cushion thickness, ² cm					
Right front lateral	0.88	0.84	0.42 - 1.61	0.20	405
Right front medial	0.91	0.90	0.30 - 1.67	0.24	410
Left front lateral	0.90	0.89	0.36 - 1.52	0.22	410
Left front medial	0.89	0.89	0.30 - 1.73	0.26	411
Right hind lateral	0.95	0.95	0.36 - 1.97	0.27	500
Right hind medial	0.90	0.90	0.30 - 1.79	0.25	496
Left hind lateral	0.98	0.96	0.24 - 1.85	0.26	501
Left hind medial	0.93	0.95	0.36 - 2.03	0.25	493

Table 1. Descriptive statistics with unadjusted summary statistics for variables offered to the multivariablemodels

¹Measured at the base of the tail.

²Measured by sole ultrasonography.

sociation with the MDCT; an $R^2 = 0.14$ was estimated by the simple linear regression model (Figure 4).

For the GLM that assessed the association of several independent variables with the MDCT (hind digits), the following variables were considered significant: BCS, lesion, parity, and MGV (Table 3). Body condition score was highly significant; the MDCT increased consistently as the BCS of the cows improved (P <(0.001). The least squares means of MDCT were (0.52)and 1.21 for BCS 1.5 and 4, respectively. Cows with lesions had significantly lower MDCT compared with cows with no lesions [0.88 (0.01) and 0.95 (0.02) respectively]. Furthermore, stage of lactation was a highly significant variable in the model; MDCT was high in the beginning of the lactation and decreased consistently, reaching its lowest value in the fourth month of lactation and gradually increasing after the fourth month of lactation (Figure 5).

The variables retained in the logistic regression model were MDCT, parity, and stage of lactation (Table 4). Cows in the 2 lowest quartiles of QDCT had greater odds of being detected with a painful foot lesion compared with the higher quartiles (P < 0.001). The adjusted prevalence of claw horn lesions was 24.4 and 8.6% for QDCT = 1 and QDCT = 4, respectively. To assess the model fit and predictability of the overall model, a ROC analysis was performed with the predicted probabilities from the model; the area under the ROC curve was 0.79 (Figure 6).

DISCUSSION

Digital cushion thickness was a strong predictor of lameness; cows in the upper quartile of DCT had an adjusted prevalence of lameness 15 percentage points lower than the lower quartile. To our knowledge, this is the first time that MDCT has been associated with risk



Figure 3. Typical ultrasonographic image that was observed in the study when performing ultrasonography at the sole ulcer site (after hoof trimming was performed). The semicircle located at the top of the image represents the boundaries of the curved array dual frequency probe, which was set at 7.5 MHz, the first echogenic line (thicker line perpendicular to the semicircle) represents the outer margin of the sole, the second echogenic line (thinner and shortest) represents the inner margin of the sole, and the third echogenic line represents the margins of the caudal aspect of the third phalanx. The distance from the inner margin of the sole (second echogenic line) to the distal edge of the third phalanx was assessed.



Figure 4. Simple linear regression scatter plot indicating the negative association of mean digital cushion thickness of the hind digits and mean gray level ($R^2 = 0.14$).

of claw horn lesion. Räber et al. (2004) described the anatomy of the bovine digital cushion and highlighted the importance of this structure to dampen compression in the heel under the distal phalanx. Additionally, it was found in the present study that the digital cushion of primiparous animals was thinner than that of multiparous cows. Räber et al. (2004) also reported that heifers had thinner digital cushions compared with cows, with a reduction again observed in older cows.

Sole ulcers and white line lesions are prevalent in North America; a combined incidence of those lesions of 23.3% has been described previously (Bicalho et al., 2008). The incidence of sole ulcers and white line disease can be dependent on the farm's production system. Nevertheless, sole ulcers and white line disease were reported to be the most prevalent claw lesions observed in lactating dairy cattle (Manske et al., 2002). Furthermore, the economic losses associated with sole ulcers and white line diseases are likely to be far greater than the losses associated with other digital diseases such as digital and interdigital dermatitis and foot rot (Warnick et al., 2001). It has been suggested that sole ulcers and white line diseases are a consequence of subclinical laminitis (Hendry et al., 1997; Thoefner et al., 2004; Vermunt, 2007). However, this belief has been challenged lately by a few different research groups

Table 2. Prevalence of hoof diseases (diagnosed by visual inspection of the digits after hoof trimming was performed) and lameness [detected by visual locomotion scoring (VLS) performed immediately before hoof trimming] by parity group

Variable	Parity 1	Parity >1	Total, n
No lesion, $\%$ (n)	84.4 (162)	58.6 (181)	343
Sole ulcer, % (n)	4.2 (8)	27.8 (86)	94
White line disease, $\%$ (n)	1.0(2)	6.5 (20)	22
Digital dermatitis, % (n)	9.9 (19)	5.2(16)	35
Toe necrosis, % (n)	0.5(1)	1.9(6)	7
Total, n	192	309	501
VLS <3, % (n)	80.2 (154)	51.8(160)	314
VLS $>3, \%$ (n)	19.8 (38)	48.2 (149)	187
Total, n	192	309	501

LAMENESS AND DIGITAL CUSHION THICKNESS

Variable	Digital cushion thickness, cm (SD)	95% Confidence interval	Regression estimate (SD)	<i>P</i> -value
Intercept	_		0.54(0.27)	
BCS 1.5	0.52(0.17)	0.18 - 0.86	-0.68(0.21)	< 0.001
BCS 2	0.86(0.03)	0.81 - 0.92	-0.34(0.12)	
BCS 2.5	0.92(0.01)	0.89 - 0.95	-0.28(0.12)	
BCS 3	0.96(0.01)	0.93 - 0.99	-0.25(0.12)	
BCS 3.5	1.03(0.03)	0.96 - 1.09	-0.18(0.13)	
BCS 4	1.21(0.12)	0.97 - 1.45		
Lesion ² present	0.88(0.01)	0.86 - 0.90		< 0.001
Lesion ² absent	0.95(0.02)	0.91 - 0.99	$0.07 \ (0.02)$	
Parity 1	0.85(0.02)	0.82 - 0.89	-0.14(0.02)	< 0.001
Parity >1	0.99(0.01)	0.97 - 1.02		
Height of the cow ³			0.005(0.002)	0.020
Mean gray value			-0.012(0.002)	< 0.001

Table 3. Outcome of the linear regression model that analyzed the effect of several independent variables on the thickness of the digital cushion (least squares means)¹

¹Data was analyzed by linear regression model that also included stage of lactation as a fixed effect. Least squares means presented in this table were adjusted by all the other variables in the model. A total of 489 cows were used for this analysis.

²Lesion = visually detected sole ulcer or white line disease after hoof trimming.

^{3}Height of the cow = the height of the cow measured at the base of the tail.

(Logue et al., 2004). Räber et al. (2004) suggested that claw horn disruption lesions could be secondary to concussions of the corium tissue because of impaired shock-absorbing properties of the digital cushion. Furthermore, hemorrhages of the sole ulcer and white line sites have been observed in the absence of laminitic lesions (Lischer et al., 2002).

In this study, it was observed that DCT is highly associated with BCS; DCT increased gradually as BCS increased. It has been reported that dairy cows experience loss of BCS in the early lactation period as a consequence of mobilizing adipose tissue, which is partitioned toward the mammary gland to support milk production (Rastani et al., 2001). The bovine digital cushion is mainly composed of adipose tissue (Räber et al., 2006). Therefore, it is biologically plausible to assume that lactating dairy cows are not only mobilizing adipose tissue from other parts of the body such as subcutaneous fat, muscle, and intraabdominal fat but also from the digital cushion. A negative linear relationship of DCT and MGV was also observed, suggesting that the composition of the digital cushion is altered as its thickness decreases. Räber et al. (2006) reported that digital cushions of cows had significantly higher lipid content compared with heifers; the fatty acid composition also differed between cows and heifers.

It has been reported in anatomical studies using postmortem specimens that sole lesions (hemorrhage and necrosis) occur in conjunction with the distal displacement of the third phalanx; most of those studies assumed that the distal displacement of the third

phalanx was originally caused by laminitis (Lischer et al., 2002). Lischer et al. (2002) measured the level of distal displacement of the third phalanx by measuring the thickness of the soft tissue from the inner surface of the horn capsule to the distal edge of the third phalanx, concluding that cows with sole ulcers had thinner digital cushions compared with controls and the difference was attributed to the distal displacement of the third phalanx. Nevertheless, the measurements taken on those studies were very similar to the ultrasonographic measurements completed in the present study. It is possible that those anatomical studies were simply assessing the thickness of digital cushion and not the level of distal displacement of the third phalanx. Furthermore, the small sample size combined with the lack of risk factor data (BCS, milk production, and stage of lactation) and appropriate analysis limited the validity of the hypothesized cause-and-effect relationships suggested in such anatomical studies. It is important to acknowledge that our study did not assess the potential movement of the third phalanx as described by Lischer et al. (2002).

There is very little evidence that severe claw horn disruption lesions such as sole ulcers and white line diseases are caused by laminitis (Logue et al., 2004). The generalization of laminitis knowledge from the equine field may have distracted the research community toward the study of laminitis in dairy cattle and, even though it is unquestionable that clinical acute laminitis is a true condition of dairy cattle (rare acute lameness affecting multiple limbs), the present study



Figure 5. Adjusted mean digital cushion thickness (MDCT) of all 4 hind digits by stage of lactation; stage of lactation was categorized in 30-d intervals with the exception of stage of lactation 10, which represents cows with DIM >270. Data were analyzed by a linear regression model that also included the following variables: BCS, lesion, parity, height, and mean gray value. The number of cows per category was 31, 36, 76, 75, 40, 88, 38, 30, 65, and 24 for stages of lactation 1 to 10, respectively.

suggests that the dimensions of the digital cushion and perhaps its composition can ultimately affect its ability to dampen pressure on the corium tissues exerted by the third phalanx. Consequently, contusions within the claw horn capsule would be more likely to happen explaining the higher prevalence of sole ulcers and white line diseases in cows with thin digital cushions that was observed in the present study.

that has attempted to assess the associations of DCT with BCS and stage of lactation; thinner cows had lower DCT. Hoedemaker et al. (2008) reported that cows with low BCS at parturition were at 9.4 times increased odds of developing lameness throughout the lactation compared with better conditioned cows. In another study the risk of foot problems after partu-

To the authors' knowledge, this is the first study

Independent variable	Adjusted prevalence of claw horn lesions, $\%$	Adjusted odds ratio	95% Confidence interval	<i>P</i> -value
$\overline{QDCT^2} = 1$	24.4	3.4	1.6-7.2	
QDCT = 2	28.1	4.1	2.1 - 8.2	
QDCT = 3	14.5	1.9	1.0 - 3.6	
QDCT = 4	8.6			
Parity 1	4.0	14.0	6.9 - 28.3	< 0.001
Parity >1	36.8			

¹The outcome variable was presence or absence of claw horn lesions and the independent variables offered to the model were digital cushion thickness (categorized in quartiles), parity number, stage of lactation, cow height, previous lactation length, and BCS. The only variables retained in the model were QDCT, parity, and stage of lactation. The estimated pseudo R^2 was 0.15. Data were analyzed by a logistic regression model that also included stage of lactation as a fixed effect. Adjusted prevalence was calculated in Stata (Stata Corp., College Station, TX) using the logistic regression probability equation. The independent variables used in the model were set to their respective mean values (general frequencies) when calculating the adjusted prevalence of the interest variables.

 2 QDCT = quartile digital cushion thickness.



Figure 6. Receiver operating characteristic curve of the predicted probability estimated by the logistic regression (independent variables were parity, digital cushion thickness, and stage of lactation) by presence or absence of a claw horn lesions lesion (sole ulcers and white line diseases) diagnosed at hoof trimming.

rition increased 7-fold for cows that were considered under-conditioned at dry off (Gearhart et al., 1990). It has been hypothesized that the aggravated negative energy balance that caused loss of body condition is the cause of increased risk of lameness (Hassall et al., 1993). The positive association of BCS and DCT found in the present study gives support to the proposal that low BCS is a risk factor for lameness, not only a consequence, as was believed up to this point. It is important to highlight that the nature of the present study design (cross-sectional study design) does not allow us to conclude that such a cause-and-effect relationship exists because it is not clear that low BCS and consequently low DCT preceded the event of lameness. However, it has been reported that a long delay from the initial instigation of the injury and the presence of a detectable claw horn lesion may be observed (Leach et al., 1997). It is possible that the sharp decrease in digital cushion diameter observed from the first to the second month of lactation causes the primary damage to the corium tissue, this damage is then chronically aggravated by the decreasing DCT, and the lesion could eventually be detected visually in the sole. It is also important to highlight the multifactorial nature of claw horn lesions; several intrinsic and extrinsic risk factors are known to be associated with the incidence of claw horn lesions. Nevertheless, the present study provides strong support to the hypothesis that claw horn disruption lesions are a consequence of contusions within the claw horn capsule. It is important to emphasize that our findings should only be generalized to dairy cows exposed to similar production systems, particularly the use of hard-surface floors and confinement.

Stage of lactation is an important risk factor of sole ulcers, and the greatest prevalence of sole ulcers was found to be around the peak of lactation (60–100 DIM; Hoedemaker et al., 2008). In the present study, it was found that DCT decreases steadily after parturition, reaching a nadir 4 mo into the lactation. The dynamics of BCS by stage of lactation have been reported to be similar to the dynamics of DCT described in the present study: BCS decreased steadily from parturition, reaching a nadir at exactly 120 DIM (Waltner et al., 1993). This finding supports the concept that low DCT is a risk factor for lameness given that most cases of claw horn disruption lesions appear to be initiated around parturition.

It has been shown recently that claw horn disruption lesions are associated with high milk production in the beginning of the lactation; in fact, lame cows produced an excess of 3 kg/d more milk compared with nonlame cows (Bicalho et al., 2008). High milk production in the beginning of the lactation can exacerbate the observed negative energy balance and consequently increase the loss of BCS within the first 100 DIM. Higher producing cows lost significantly more BCS from parturition to 60 DIM than did lower producing cows (Waltner et al., 1993). Therefore, high milk yield in the beginning of the lactation can be a risk factor for claw horn lesions because high-producing cows may have lower BCS and consequently thinner digital cushions. However, it is important to note that high milk yield might be associated with claw horn lesions by potentially increasing hoof growth rate, high DMI, and subclinical ruminal acidosis. Additional longitudinal research is needed to clarify the role that high milk production plays in the pathogenesis of claw horn lesions.

CONCLUSIONS

The prevalence of sole ulcers and white line diseases was significantly associated with DCT; cows with low DCT were at a higher risk of claw horn lesions. Body condition scores were positively associated with DCT. Furthermore, DCT decreased steadily from parturition, reaching a nadir 120 d after parturition. These findings support the concept that sole ulcers and white line diseases are related to contusions within the claw horn capsule, and such contusions are at least in part a consequence of the lower capacity of the digital cushion to dampen the pressure exerted by the third phalanx on the soft tissue beneath.

REFERENCES

- Bazeley, K., and P. J. Pinsent. 1984. Preliminary observations on a series of outbreaks of acute laminitis in dairy cattle. Vet. Rec. 115:619–622.
- Bicalho, R. C., S. H. Cheong, G. Cramer, and C. L. Guard. 2007a. Association between a visual and an automated locomotion score in lactating Holstein cows. J. Dairy Sci. 90:3294–3300.
- Bicalho, R. C., F. Vokey, H. N. Erb, and C. L. Guard. 2007b. Visual locomotion scoring in the first seventy days in milk: Impact on pregnancy and survival. J. Dairy Sci. 90:4586–4591.
- Bicalho, R. C., L. D. Warnick, and C. L. Guard. 2008. Strategies to analyze milk losses caused by diseases with potential incidence throughout the lactation: A lameness example. J. Dairy Sci. 91:2653–2661.
- Booth, C. J., L. D. Warnick, Y. T. Grohn, D. O. Maizon, C. L. Guard, and D. Janssen. 2004. Effect of lameness on culling in dairy cows. J. Dairy Sci. 87:4115–4122.
- Edmonson, A. J., I. J. Lean, L. D. Weaver, T. Farver, and G. Webster. 1989. A body condition scoring chart for Holstein dairy cows. J. Dairy Sci. 72:68–78.
- Fjeldaas, T., O. Nafstad, B. Fredriksen, G. Ringdal, and A. M. Sogstad. 2007. Claw and limb disorders in 12 Norwegian beef-cow herds. Acta Vet. Scand. 49:24–35.
- Garbarino, E. J., J. A. Hernandez, J. K. Shearer, C. A. Risco, and W. W. Thatcher. 2004. Effect of lameness on ovarian activity in postpartum Holstein cows. J. Dairy Sci. 87:4123–4131.
- Gearhart, M. A., C. R. Curtis, H. N. Erb, R. D. Smith, C. J. Sniffen, L. E. Chase, and M. D. Cooper. 1990. Relationship of changes in

condition score to cow health in Holsteins. J. Dairy Sci. 73:3132–3140.

- Greenough, P. R., and A. D. Weaver. 1997. Lameness in Cattle. 3rd ed. W. B. Saunders. Philadelphia, PA.
- Hassall, S. A., W. R. Ward, and R. D. Murray. 1993. Effects of lameness on the behavior of cows during the summer. Vet. Rec. 132:578–580.
- Hendry, K. A., A. J. MacCallum, C. H. Knight, and C. J. Wilde. 1997. Laminitis in the dairy cow: A cell biological approach. J. Dairy Res. 64:475–486.
- Hernandez, J., J. K. Shearer, and D. W. Webb. 2001. Effect of lameness on the calving-to-conception interval in dairy cows. J. Am. Vet. Med. Assoc. 218:1611–1614.
- Hoedemaker, M., D. Prange, and Y. Gundelach. 2008. Body condition change ante- and postpartum, health and reproductive performance in German Holstein cows. Reprod. Domest. Anim. 44:167–173.
- Kossaibati, M. A., and R. J. Esslemont. 1997. The costs of production diseases in dairy herds in England. Vet. J. 154:41–51.
- Leach, K. A., D. N. Logue, S. A. Kempson, J. E. Offer, H. E. Ternent, and J. M. Randall. 1997. Claw lesions in dairy cattle: Development of sole and white line haemorrhages during the first lactation. Vet. J. 154:215–225.
- Lischer, C., P. Ossent, M. Räber, and H. Geyer. 2002. Suspensory structures and supporting tissues of the third phalanx of cows and their relevance to the development of typical sole ulcers (Rusterholz ulcers). Vet. Rec. 151:694–698.
- Logue, D. N., J. E. Offer, and R. D. McGovern. 2004. The bovine digital cushion-how crucial is it to contusions on the bearing surface of the claw of the cow? Vet. J. 167:220–221. Manske, T., J. Hultgren, and C. Bergsten. 2002. Prevalence and
- 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.
- Mill, J. M., and W. R. Ward. 1994. Lameness in dairy cows and farmers' knowledge, training and awareness. Vet. Rec. 134:162–164.
- Räber, M., C. Lischer, H. Geyer, and P. Ossent. 2004. The bovine digital cushion–A descriptive anatomical study. Vet. J. 167:258– 264.
- Räber, M., M. R. Scheeder, P. Ossent, C. Lischer, and H. Geyer. 2006. The content and composition of lipids in the digital cushion of the bovine claw with respect to age and location–A preliminary report. Vet. J. 172:173–177.
- Rastani, R. R., S. M. Andrew, S. A. Zinn, and C. J. Sniffen. 2001. Body composition and estimated tissue energy balance in Jersey and Holstein cows during early lactation. J. Dairy Sci. 84:1201– 1209.
- Sprecher, D. J., D. E. Hostetler, and J. B. Kaneene. 1997. A lameness scoring system that uses posture and gait to predict dairy cattle reproductive performance. Theriogenology 47:1179–1187.
- Tarlton, J. F., D. E. Holah, K. M. Evans, S. Jones, G. R. Pearson, and A. J. Webster. 2002. Biomechanical and histopathological changes in the support structures of bovine hooves around the time of first calving. Vet. J. 163:196–204.
- Thoefner, M. B., C. C. Pollitt, A. W. Van Eps, G. J. Milinovich, D. J. Trott, O. Wattle, and P. H. Andersen. 2004. Acute bovine laminitis: A new induction model using alimentary oligofructose overload. J. Dairy Sci. 87:2932–2940.
- van Amstel, S. R., F. L. Palin, and J. K. Shearer. 2004. Measurement of the thickness of the corium and subcutaneous tissue of the hind claws of dairy cattle by ultrasound. Vet. Rec. 155:630–633.
- Vermunt, J. J. 2007. One step closer to unravelling the pathophysiology of claw horn disruption: For the sake of the cows' welfare. Vet. J. 174:219–220.
- Waltner, S. S., J. P. McNamara, and J. K. Hillers. 1993. Relationships of body condition score to production variables in high producing Holstein dairy cattle. J. Dairy Sci. 76:3410–3419.
- Warnick, L. D., D. Janssen, C. L. Guard, and Y. T. Grohn. 2001. The effect of lameness on milk production in dairy cows. J. Dairy Sci. 84:1988–1997.