A longitudinal study of digital cushion thickness and its function as a predictor for compromised locomotion and hoof lesions in Holstein cows

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ABSTRACT: Lameness is a major animal welfare and economic issue for the dairy industry and is a challenge to overcome due to multifaceted causes. Digital cushion thickness (**DCT**) is a strong predictor of lameness and is phenotypically associated with incidence of claw horn disruption lesions (**CHDL**; sole ulcers and white line disease). We hypothesized that DCT varies between digits and across lactation within the cow. This variation could be characterized to predict the occurrence of CHDL or compromised locomotion. BCS, visual locomotion score (**VLS**), DCT, and presence or absence of lesions were collected at 4 time points: <40 d prepartum (**DPP**), 1 to 30 d in milk (**DIM**), 90 to 120 DIM, and ≥255 DIM for 183 commercial Holstein cows enrolled in the study. Cows underwent digital sonographic examination for the measurement of DCT evaluated at the typical sole ulcer site beneath the flexor tuberosity for the right front medial and lateral digits and right hind medial and lateral digits. Factors such as parity number and stage in lactation were obtained from farm management software (DairyComp 305; Valley Agricultural Software, Tulare, CA). Cows were grouped by parity: primiparous (parity = 1) or multiparous (parity ≥ 2). The prevalence of CHDL among time points ranged from 0% to 4.2% for primiparous cows vs. 2.5% to 25% for multiparous cows, whereas the prevalence of lameness based on VLS of 3 to 5 ranged from 1.7% to 8.3% for primiparous cows vs. 12.7% to 33% for multiparous cows. DCT varied within primiparous and multiparous cows based on stage of lactation and digit ($P < 0.05$) and was thicker for both parity groups prior to dry off (≥255 DIM) and thinnest prior to calving (<40 DPP) and after peak lactation (90 to 120 DIM). The DCT of the front medial digit was thickest for primiparous heifers, whereas the hind lateral digit was thickest for multiparous cows. The DCT of the hind medial digit was thinnest for both parity groups. Parity group and DCT of the hind lateral digit <40 DPP were important predictors of CHDL ($P < 0.05$), whereas parity group and DCT of the hind lateral digit and front lateral digit at 1 to 30 DIM were key predictors of VLS lameness ($P < 0.05$). These results may help identify animals with higher odds of developing these diseases by highlighting key time points and specific digits of importance for monitoring. In addition, it improves our biological understanding of the relationship between DCT and lameness.

Key words: claw horn disruption lesion, dairy cow, digital cushion, hoof lesion, lameness

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INTRODUCTION

Improvements in animal welfare are a priority for the animal agricultural industry that benefit both animals and producers. There is a growing concern for the well-being of animals in response to the demand of consumers for welfare-certified products (Bicalho et al., 2009). Lameness is a debilitating condition that challenges the sustainability of production systems due to the pain and ensuing animal welfare issues, along with significant economic losses (Warnick et al., 2001; Vermunt, 2007). It is defined as the clinical presentation of impaired locomotion, regardless of cause; is caused by a variety of diseases, such as noninfectious and infectious hoof lesions; and is influenced by environmental and genetic factors (Archer et al., 2010). Estimated costs for lameness range from US$120 to US$500 per case with specific diseases, such as sole ulcers, averaging US$220 per case (Cha et al., 2010).

The multifaceted nature of lameness makes it a difficult problem to solve. However, digital cushion thickness (**DCT**) has been shown to be a strong predictor of lameness and claw horn lesions (Bicalho et al., 2009). The digital cushion is an important structure in dampening the compression in the heel under the distal phalanx (Räber et al., 2004). Prolonged exposure to concrete surfaces causes the solar surface of the hind lateral claw to flatten and increase in width, changing the dynamics inside the claw. Instead of confining weight-bearing to the wall, part of the weight load is transferred to the central part of the sole creating abnormal pressure (Mülling and Greenough, 2006). If the digital cushion is not thick enough to act as a barrier, this pressure could cause more problems, most notably, claw horn disruption lesions (**CHDL**); e.g., sole ulcers and white line disease. Therefore, the objectives of this study were 1) to determine the variation of DCT within the cow across lactation and between digits, and 2) to determine the optimal variables of time point and digit to measure DCT for predicting lameness defined by visual locomotion score (**VLS**) and CHDL.

MATERIALS AND METHODS

Approval from the Cornell University Institutional Animal Care and Use Committee (Protocol 2014-0121) and signed owner consent were obtained prior to commencement of this study.

Study Herd

Data were collected from a single dairy farm located near Ithaca, NY, from October 13, 2015 to September 27, 2016. The farm milked 3,800 Holstein cows three times daily in a 100-cow rotary milking parlor. The lactating cows were kept in 10 housing pens that had deep-bedded free-stalls filled with anaerobically digested and separated manure solids with quicklime. The barn alleys had grooved-concrete flooring and were cleaned by manual scrapers. All the walkways to and from the milking parlor and the holding pen were covered with rubber. The walk from a pen to the parlor ranged from 181 to 534 m. The cows stood an average of 1 h for each milking. Footbaths were located in the exit lanes of the milking parlor. Each cow was scheduled to receive routine hoof trimming twice yearly based on a farm protocol created in DairyComp 305 (Valley Agriculture Software, Tulare, CA) that selected cows for routine trimming once they were past 150 d since last routine trimming. In addition, all cows received routine hoof trimming at dry off. Lame cows were identified by visual detection of an asymmetric gait when returning from the milking parlor. A systematic lameness scoring system was not utilized. The lame cows were evaluated and treated that same evening.

Data Collection and Study Design

A total of 183 animals were conveniently enrolled and sampled in a prospective cohort study targeting 245 to 270 d carried calf (**DCC**) on 10 enrollment days. The cows were followed throughout their subsequent lactation, with DCT measurements performed at four time points (Table 1). Time points were chosen in an aim to measure DCT when it was likely thinnest, thickest, and corresponding to physiological changes over lactation that might effect DCT. However, ranges in the targeted time periods were affected as farm hoof trimming schedules were accommodated. The first measurement was taken <40 d prepartum (**DPP**), targeting improved body condition prior to calving. Fifty-nine nulliparous cows were evaluated during their regular trimming when they were moved to the close-up pen at 240 to 260 DCC, whereas 118 multiparous cows were evaluated 248 to 267 DCC. The second measurement occurred post calving at 8 to 34 d in milk (**DIM**) with the cow in presumed energy deficit. The third measurement occurred mid lactation at 93 to 118 DIM when Bicalho et al. (2009) found DCT to be thinnest. The fourth measurement occurred during late lactation at ≥255 DIM with a range of 255 to 335 DIM and a mean of 285 DIM. The large range in sampling time related to when cows became pregnant and therefore when they were going to be dried off. This event aimed at measuring cows as their

Table 1. Descriptive statistics of cow height and summary statistics of the number of cows at each measurement time point for DCT separated by parity group[1]

		Parity		Descriptive statistics			
Variable	Time point	Primiparous[2], *n*	Multiparous, *n*	Mean	SD	Min	Max
Cow height[3], cm				146	4	137	156
<40 DPP	1	59	118				
8 to 34 DIM	2	59	109				
93 to 118 DIM	3	52	97				
≥255 DIM	4	48	76				

[1]Cows were from one large commercial farm in New York.

[2]Nulliparous animals at <40 DPP transitioned to primiparous for all time points afterward.

[3]Assessed as the average of both the distance from the floor to the withers and the floor to the dorsal aspect of the caudal sacral joint.

milk production was decreasing prior to dry off and they were expected to have regained body condition. The third and fourth time points also coincided with routine hoof trimming schedules to minimize impact on the cows and farm management.

Hoof trimming was completed by three trained farm employees. One trimmer was responsible for cows in lactation whereas two trimmers handled the nulliparous animals prior to calving. The two trimmers worked simultaneously, consistently trimming either the front or hind foot, respectively. Cows were restrained for hoof trimming using two types of standing hoof trimming chutes. The first measurement was carried out using an HSeries Chute (Comfort Hoof Care, Baraboo, WI), and the other three measurements were carried out using an Appleton Steel Trimming Chute (Appleton Steel, Appleton, WI).

Measures, including BCS, height, and lesion presence, were recorded based on their potential for affecting DCT or lameness. The BCS ranged from 1 to 5 with a quarter point system as described by Edmonson et al. (1989). The VLS ranged from 1 to 5 with 1 = normal, 2 = presence of a slightly asymmetric gait, 3 = cow moderately favors 1 or more limbs, 4 = severely lame, and 5 = non-weight-bearing lame (Sprecher et al., 1997; Bicalho et al., 2007). Both were assessed and collected by the same researcher at each time point to minimize rater variability. A binary lesion score was determined by farm records: 0 = no new lesion, 1 = new lesion. The lesion score was determined based on the DCT measurement intervals. Lesion score for the first measurement was based on the presence or absence of a new lesion from the time the animal was enrolled until the parturition date. Lesion scores for the second, third, and fourth measurements were determined from 1 to 30 DIM, 31 to 120 DIM, and 121 DIM to the date of the last measurement, respectively. Cow height, assessed as both the distance from the floor to the withers and the floor to the dorsal aspect of the caudal sacral joint, was measured at the beginning and end of the study. Parity, DIM at each measurement event, and parturition date were obtained from the farm management software.

The cows 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. If the time point was coincident with hoof trimming, the digital cushion measurement was taken immediately after being trimmed. The measurement was always performed at the typical sole ulcer site located beneath the flexor tuberosity in the medial aspect of the middle pad evaluating the distance from the inner margin of the sole to the distal edge of the tuberculum flexorum of the third phalanx (Figure 1; Bicalho et al., 2009). Ultrasonography of only the right digits of both front and hind limbs were assessed. The ultrasound machine settings (i.e., depth, echo-amplification, persistence, pre- and post-processing) were kept unchanged throughout the study.

Variable Definitions

To facilitate analysis and interpretation, the variables of BCS, average height, VLS, and DCT were categorized into terciles with thresholds based on the given dataset (Oikonomou et al., 2013; Bludau et al., 2014; Mahen et al., 2018). The BCS were categorized as BCS Group 1 if BCS < 3, BCS Group 2 if BCS = 3 or 3.25, and BCS Group 3 if BCS > 3.25. Average height of each cow was categorized as short if average height < 144 cm, average if average height ≤ 148 cm and ≥ 144 cm, or tall if average height > 148 cm. The VLS were categorized as LAME = 1 for those with VLS < 3, whereas LAME = 2 for those with VLS ≥ 3. All variables

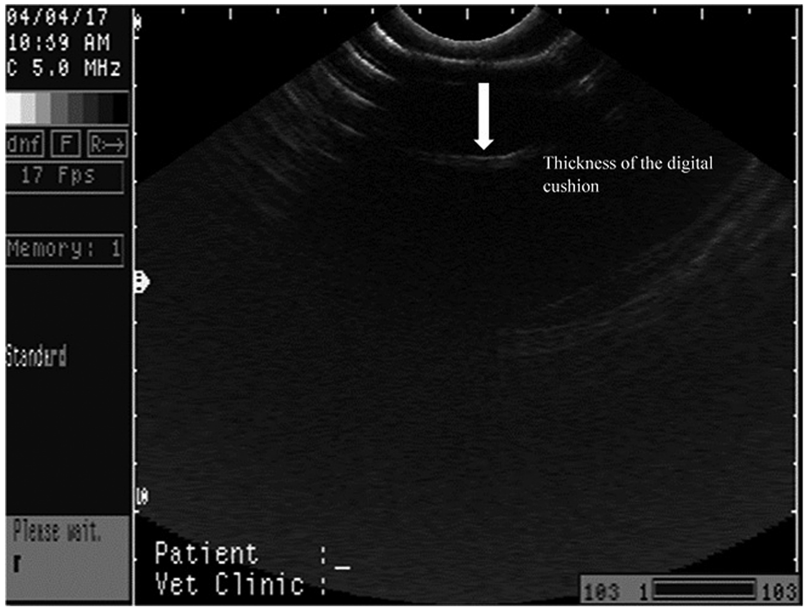

Figure 1. Typical ultrasonographic image that was observed in the study at the sole ulcer site beneath the flexor tuberosity in the medial aspect of the middle pad. The thinner and shortest echogenic line at the top of the arrow represents the inner margin of the sole, and the larger, longer, and brighter echogenic line at the bottom of the arrow represents the margins of the distal edge of the third phalanx. The distance between these lines measured represented the thickness of the digital cushion.

relating to DCT were categorized into terciles based on pooling the data from all digits: thin if DCT < 0.96 cm, average if DCT ≤ 1.19 cm and ≥ 0.96 cm, or thick if DCT > 1.19 cm.

Furthermore, the variables of time point, parity, and digit or claw (denoted as **CLAW**) were created. Time point ranged from 1 to 4 representing the four measurement time points. The variable parity = 1 represented those in their first lactation and parity = 2 for those with lactation >1. The variable CLAW represented the specific hoof digits and was categorized as CLAW = FM for front medial digit, CLAW = FL for front lateral digit, CLAW = HM for hind medial digit, and CLAW = HL for hind lateral digit. The variable of employee conducting the hoof trimming was not included in the models as it coincided with time point, distinguishing the one trimmer who did not do time point 1 nulliparous cows, and CLAW, distinguishing the two trimmers who consistently trimmed either the front or hind foot for the nulliparous cows.

Statistical Analysis

To determine whether DCT varied across lactation or differed between digits, two linear mixed models (**LMM**) were fitted to the data using PROC MIXED in SAS (SAS Institute Inc., Cary, NC). The first LMM included random effects of CLAW nested within cow to control for repeated measures and multiple measurements from each cow (four digits evaluated each time) using a compound symmetry covariance structure. Similarly, the second LMM included the random effect of time point nested within cow to control for repeated measures and the multiple measurements collected from each cow (four measurement time points per claw). Parity group, time point or CLAW, and their interaction term were included in the models as fixed effects. Pairwise mean comparisons were calculated for the statistically significant effects in both models, adjusting *P*-values for multiple comparisons using Tukey–Kramer method. The assumptions of homogeneity, normality, and independence of the residuals for both mixed models were met.

To predict the occurrence of the outcomes CHDL and lameness (VLS ≥ 3), several multiple logistic regression models were fitted in JMP Pro 12 (SAS Institute Inc., Cary, NC) to see which measurement time point of DCT was most predictive of later development of CHDL and lameness (VLS ≥ 3). Both outcomes were binary (0 = no event, 1 = at least one CHDL or VLS event, respectively, in lactation after the second measurement). Varying days at risk were accounted for in both models by including the number of measurement time points completed as a covariate time at risk (**TRISK**). For predicting CHDL, 11 cows were excluded because they either started with a CHDL or had a CHDL prior to their first measurement in lactation at 1 to 30 DIM. For predicting lameness based on VLS, 34 cows were excluded because they either were lame at enrollment or were lame at their first measurement in lactation at 1 to 30 DIM.

After categorization, potential model covariates, including parity, average height, BCS group, and the four digital cushion measurements from <40 DPP and 1 to 30 DIM, were tested for association with CHDL or lameness (VLS ≥ 3) using univariate analysis using JMP Pro 12, and any variable with Pearson x^2 $P < 0.2$ was offered to the multiple logistic regression model for predicting either CHDL or lameness (VLS ≥ 3). Multicollinearity was checked between the variables being offered to the model such that if a relationship was found (Kappa or Gamma ≥ 0.3), multiple iterations of the same model were run offering a different combination of covariates to determine which to retain. Manual backward stepwise regression was used to refine the model such that variables were discarded one by one starting with the largest *P*-value until all terms in the model had a $P < 0.05$. All biologically plausible two-way interactions with >5 observations per cell were tested. To assess the model fit and overall predictability of the logistic regression models, a receiver operating characteristic curve analysis was performed. The final model was chosen based on the highest area under the curve (**AUC**) for model predictability and on-farm application.

RESULTS AND DISCUSSION

A total of 183 animals were enrolled in the study, with 177 included in the final dataset. Table 1 depicts the number of primiparous and multiparous cows at each measurement time point. Lactation ranged from 1 to 7 in this study with a median of three lactations. Overall, six cows were removed from the study due to one of the following: they were measured <245 DCC or >270 DCC, >40 DPP, did not have an ear tag, or had dangerous behavioral problems. For the last measurement (≥255 DIM), 124 animals remained. Those that left prior to the fourth measurement were either culled by the farm or died. The actual measurement time points were <40 DPP, 8 to 34 DIM, 93 to 118 DIM, and ≥255 DIM.

The prevalence of CHDL among measurement time points ranged from 0% to 4.2% for primiparous cows and from 2.5% to 25% for multiparous cows (Figure 2A), whereas the prevalence of lameness based on VLS of 3 to 5 ranged from 1.7% to 8.3% for primiparous cows and from 12.7% to 33% for multiparous cows (Figure 2B). Multiparous cows had the highest prevalence of CHDL ≥ 255 DIM and the highest prevalence of VLS lameness between 90 and 120 DIM. Many studies have reported higher odds of claw horn lesions for older cows in mid and late lactation, as well as a higher prevalence of lameness in general (Bicalho et al., 2007; Barker et al., 2009; Machado et al., 2011; Solano et al., 2016). This could be a downstream effect of the mobilization of adipose tissues, such as the digital cushion, when the animals go through energy deficit during early lactation because sole ulcers and white line disease occur 8 to 12 wk or more after the initial event (Rastani et al., 2001; Räber et al., 2006; Shearer and Van Amstel, 2017). The prevalence of postpartum diseases associated with excessive lipolysis, such as ketosis, displaced abomasum, and metritis, have been reported higher in multiparous compared to primiparous cows (Markusfeld, 1987; Humer et al., 2016). Primiparous cows are in a different metabolic state than multiparous cows because they need nutrients for their continual growth in addition to producing milk (Wathes et al., 2007).

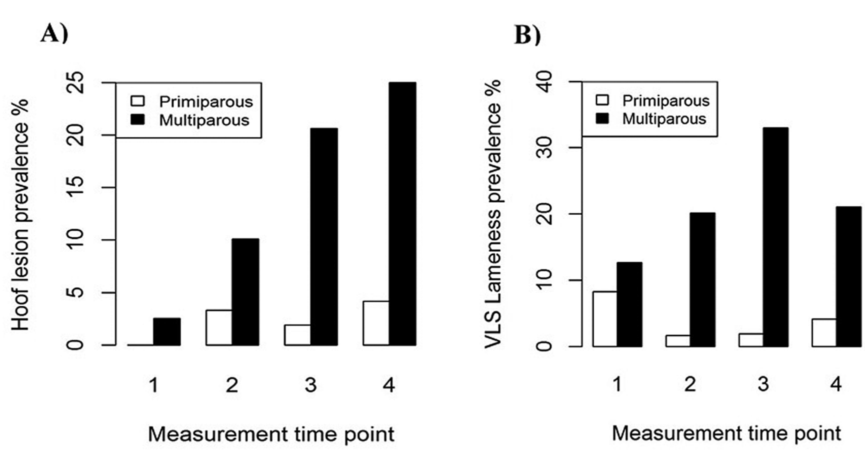

Figure 2. Prevalence of (A) hoof lesions and (B) VLS lameness at each measurement time point by parity group. The lesions included were sole ulcers and white line disease, known together as CHDL. Lameness was defined as animals with VLS ≥3. The number of primiparous cows at each measurement time point was 60, 60, 52, and 48, respectively. The number of multiparous cows at each measurement time point was 118, 109, 97, and 76, respectively. Time points correspond to 1) <40 DPP, 2) 1 to 30 DIM, 3) 90 to 120 DIM, and 4) ≥255 DIM.

Lameness prevalence of multiparous cows in the dry period (12.7%) was similar to the prevalence described by Vergara et al. (2014), who reported a mean prevalence of 11.2% (ranging from 8.7% to 13.4%) for dry cows in four large commercial free-stall herds in New York and Wisconsin, as well as Foditsch et al. (2016) who reported an average prevalence of 14% for dry cows in 23 large, high-producing commercial herds in New York. The higher prevalence of lameness and CHDL in multiparous cows could also be due to changes in the integrity of the anatomy of the bovine claw. As a cow gets older and experiences lameness and lesion events, the integrity of her claw is changed. Newsome et al. (2016) demonstrated the presence of increased new bone growth on the flexor tuberosity of the distal phalanx in cows that suffered more lameness and CHDL throughout life. These bone spurs on the bottom of the distal phalanx could be continuously pinching the digital cushion, thus altering the ability of the digital cushion to dissipate the forces acting on the claw structures, changing the adipose tissue to connective scar tissue (Räber et al., 2004). In addition, prolonged exposure to hard surfaces, trauma, and multiple experiences of metabolic and hormonal changes around calving decrease claw horn quality (Cook and Nordlund, 2009).

Least squares means for DCT by measurement time point and parity are summarized in Table 2. DCT varied by time point depending on parity group ($P < 0.01$). DCT was found to be thickest for both parity groups at ≥255 DIM compared to the other measurement time points ($P < 0.05$). This measurement occurred at the end of lactation right before dry off, a time when cows should be producing less milk and have higher body condition. The measurement time points with thinnest DCT of primiparous animals occurred <40 DPP and 90 to 120 DIM ($P < 0.05$). The first measurement was close to parturition when there are multiple demands for energy, such as the cow preparing for milk production and heifer growth, which may result in mobilizing fat reserves. In addition, this measure differed by hoof trimmer with two staff trimming either the front or hind foot respectively for nulliparous cows, while a third trimmer did the cows in lactation, which included multiparous cows for time point 1 and all cows for times points 2 to 4. Although the variable of hoof trimmer is noted, we expect that it is of less impact because two trimmers were used at this time point. The latter measurement is when energy balance is being restored and cows are beginning to gradually recover BCS until the end of lactation (Machado et al., 2010). In addition, multiparous cows had thin DCT at 1 to 30 DIM ($P < 0.05$), possibly due to them reaching peak lactation quicker and producing more milk than primiparous cows (Ray et al., 1992; Coffey et al., 2006).

Least squares means for DCT per CLAW by parity are summarized in Table 3. DCT varied by CLAW depending on parity ($P < 0.01$). This variation is likely reflective of the comparison of two digits measured from the right front hoof while the other two digits were measured from the right hind hoof. It is known that 60% of a cow's body weight is borne by the forelimbs, meaning there is an unequal distribution of weight, which could cause differences in DCT of the front vs. hind digits (Bergsten

Table 2. Least squares means (LSM) and SEM for DCT per measurement time point separated by parity group[1]

	Primiparous[2]		Multiparous	
Measurement	LSM, cm	SEM	LSM, cm	SEM
<40 DPP	0.96^{ey}	0.02	1.11^{bcdz}	0.01
1–30 DIM	1.09^{cdy}	0.02	1.07^{dy}	0.01
90–120 DIM	0.94^{ey}	0.02	1.12^{bcz}	0.02
≥255 DIM	1.18^{aby}	0.02	1.21^{ay}	0.02

[1]Data were analyzed by LMM that included the random effect of claw nested within cow and the terms parity and time point. LSM presented in this table are from the interaction of parity group and time point. A total of 177 cows were included in this analysis.

[2]Nulliparous animals at <40 DPP transitioned to primiparous for all time points afterward.

[a–e]LSM within a column with different superscripts are different at Tukey–Kramer adjusted $P < 0.05$, and if at least one superscript is the same, then the LSM are the same.

[y,z]LSM within a row with different superscripts are different at Tukey–Kramer adjusted $P < 0.05$.

Table 3. Least squares means (LSM) and SEM for DCT per claw by parity group[1]

	Primiparous[2]		Multiparous	
Claw	LSM, cm	SEM	LSM, cm	SEM
Front medial	1.14^{aby}	0.02	1.14^{by}	0.01
Front lateral	1.05^{cdy}	0.02	1.11^{bcy}	0.01
Hind medial	0.91^{ey}	0.02	1.05^{dz}	0.01
Hind lateral	1.05^{cdy}	0.02	1.18^{az}	0.01

[1]Data were analyzed by LMM that included the random effect of time point nested within cow and the terms parity and claw. LSM presented in this table are from the interaction of parity group and claw. A total of 177 cows were included in this analysis.

[2]Nulliparous animals at <40 DPP transitioned to primiparous for all time points afterward.

[a–e]LSM within a column with different superscripts are different at Tukey–Kramer adjusted $P < 0.05$, and if at least one superscript is the same, then the LSM are the same.

[y,z]LSM within a row with different superscripts are different at Tukey–Kramer adjusted $P < 0.05$.

et al., 2007). Both parity groups had the thinnest DCT in the hind medial digit ($P < 0.05$). This may be explained by the majority of cows being cow-hocked in the hind causing the toes to point out and displace more weight on the inner claws (Shearer et al., 2012). The hind medial claw lands more underneath the animal when walking or standing, thus dispersing the load of weight and pressure on the outside hoof wall where the suspension of the laminar folds exists (Toussaint Raven, 1989).

Among the four digits measured, the hind lateral digit had the thickest DCT for multiparous cows ($P < 0.05$) vs. the front medial digit in primiparous cows ($P < 0.05$). The medial claw of the forelimbs bear more weight and incur more lesions than the lateral claws, whereas the reverse is true in the hind limbs (Toussaint Raven, 1989; Murray et al., 1996; Van der Tol et al., 2002). Nuss et al. (2011) discovered the front medial claws resembled the lateral hind claws in claw length and sole length. The inside front claw might be thickest for those in their first parity because they have less weight in their hind limbs because their udders are not as large as the older cows. When the udders are large, they displace the closeness of the hind limbs and cause the surface area of the solar surface of the lateral claw to increase in width (Bergsten et al., 2007).

The final lameness (VLS ≥ 3) logistic regression model included the terms parity, DCT of the front lateral digit and hind lateral digit at 1 to 30 DIM, and TRISK with AUC of 0.83 (Table 4), whereas the final CHDL logistic regression model included the terms parity, DCT of the hind lateral digit at <40 DPP, and TRISK with AUC of 0.79 (Table 5).

Table 4. Contrast odds ratios (OR), CI, and *P*-values reported for the final lameness logistic regression model based on VLS[1]

Variable	Contrast	OR	95% CI	*P*-value
Parity	Multiparous–primiparous	8.9	2.4–46.9	<0.01
FL2[2]	Average–thin	11.5	2.4–91.8	<0.01
	Thick–thin	5.5	0.8–54.7	0.09
	Average–thick	2.0	0.6–9.1	0.27
HL2[3]	Thin–average	10.7	2.6–56.5	<0.01
	Thin–thick	6.6	1.8–28.7	<0.01
	Thick–average	1.6	0.4–7.1	0.48

[1]The outcome variable was the occurrence of a lameness event based on VLS in lactation following the DCT measurement. The independent variables retained in the final model were parity, DCT of the front lateral digit and hind lateral digit at 1 to 30 DIM, and time at risk. A total of 143 cows were included in this analysis.

[2]FL2 = front lateral DCT measured at the second time point at 1 to 30 DIM.

[3]HL2 = hind lateral DCT measured at the second time point at 1 to 30 DIM.

The DCT of the hind lateral digit and parity group were important predictors in both models ($P < 0.05$). Multiparous cows had higher odds of a CHDL or lameness (VLS ≥ 3) event in lactation of the study period compared to primiparous cows ($P < 0.01$). Cows with a thin DCT of the hind lateral digit <40 DPP had five times greater odds of a CHDL event compared to cows with an average DCT of the same digit ($P = 0.01$). Cows with a thin DCT of the hind lateral digit within the first month post-calving had 10.7 times greater odds of a lameness event compared to cows with an average DCT of the same digit ($P < 0.01$) and 6.6 times greater odds of a lameness event compared to cows with a thick DCT of the same digit ($P < 0.01$).

As opposed to the inner hind claw, the load on the outside hind claw is greater and abnormal due to conformation shifting the pressure landing on the middle sole rather than the hoof wall. Walking on concrete causes the wall to be worn down and a disproportionate amount of the sole bears weight (Bergsten et al., 2007). This sole contains the digital cushion rather than the suspension needed to bear the weight. Exposure to concrete surfaces for long periods of time causes trauma and inflammation that can create changes to the distal phalanx, such as the bone spurs mentioned earlier, which in turn affects the digital cushion such that the adipose tissue becomes scar tissue and it loses its cushioning capacity (Räber et al., 2004; Mülling and Greenough, 2006; Newsome et al., 2016).

Having thin DCT of the outside hind digit increased the odds of a CHDL or lameness (VLS ≥ 3) event. Due to the unequal distribution of weight and pressure on the lateral hind digit and other reasons mentioned, a thin digital cushion has more trouble acting as a barrier between the distal phalanx and the sole; hence, problems such

Table 5. Contrast odds ratios (OR), CI, and *P* values reported for the final CHDL logistic regression model[1]

Variable	Contrast	OR	95% CI	*P*-value
Parity	Multiparous–primiparous	7.3	2.3–28.7	<0.01
HL1[2]	Thin–average	5.0	1.5–19.9	0.01
	Thin–thick	1.6	0.6–4.7	0.36
	Thick–average	3.1	0.9–12.4	0.07

[1]The outcome variable was the occurrence of CHDL in lactation following the DCT measurement. The independent variables offered to the final model were parity, DCT of the front lateral digit and hind lateral digit at <40 DPP, and time at risk. The variables retained in the model were parity, DCT of the hind lateral digit at <40 DPP, and time at risk. A total of 166 cows were included in this analysis.

[2]HL1 = hind lateral DCT measured at the first time point <40 DPP.

as lameness or claw horn lesions develop (Van der Tol et al., 2003). This is especially important right before calving and in the month following calving when the cow has undergone the stressful event of giving birth and has been exposed to periparturient hormones, such as relaxin and estrogen (Tarlton et al., 2002). Relaxin is known to distend the reproductive tract for parturition and can have an effect on other structures throughout the body involving connective tissue, likely causing the distal phalanx to sit lower within the hoof capsule exerting more pressure on the digital cushion (Tarlton et al., 2002; Bicalho and Oikonomou, 2013; Newsome et al., 2017).

The forelimb has not been studied as greatly as the hind limb because over 90% of hoof lesions causing lameness occur in the hind limbs, mostly in the lateral claw (Bergsten et al., 2007; Shearer et al., 2012). Although the results presented here agree with the importance of the hind lateral claw, they also reveal the importance of claws in the forelimb. DCT of the front lateral digit at 1 to 30 DIM was an influential predictor of a lameness (VLS ≥ 3) event in lactation, with cows having 11.5 times greater odds of lameness if their DCT was average compared to thin ($P < 0.01$). This could be due to CHDL possibly being present when the measurement was taken even though the individual was not demonstrating impaired locomotion. Newsome et al. (2017) discovered the thickness of the digital cushion to be greater when a sole ulcer was present due to increased vascularization, edema, or inflammation in the underlying tissues. Furthermore, the average thickness of the digital cushion could be due to the quality of the tissue and may reflect hard scar tissue rather than soft adipose tissue (Räber et al., 2004).

This study determined DCT of the front lateral digit to be important in predicting subsequent lameness. Newsome et al. (2017) uniquely related DCT to back fat thickness. However, they assessed the digital cushion differently in that they measured sole soft tissues at three different sites. Both Newsome et al. (2017) and the current study found DCT to be thickest about 8 wk prepartum when the animals are near or starting the dry off period. This study did find measurements of DCT taken 1 to 30 DIM to be important predictors of subsequent VLS lameness occurrence.

It is important to note that one of the main limiting factors of this study was that it assessed only 178 animals from a single large commercial herd in Upstate New York. In addition, the current study was unable to investigate the relationship between DCT and specific diseases separately, such as sole ulcer and white line disease, due to the low prevalence of each type of lesion. Similarly, BCS lacked sufficient variation to be informative.

This study determined which claws are more important to measure and at what time in lactation they are most informative to identify animals more prone to developing CHDL or experiencing a lameness event later in lactation despite these limitations. If producers measure the DCT of a hind and front lateral digit within the first month after parturition, then this may help them identify cows with a higher odds of developing CHDL or a VLS lameness event. This could allow producers to monitor those cows more closely and adjust management practices such that CHDL and lameness are prevented or detected early enough to alleviate pain, improve resolution of lameness, avoid possible major changes to the hoof structures, and prevent negative downstream effects like decreased productivity.

An additional longitudinal study targeting dry off (<140 DPP) and 90 to 120 DIM, which correlated to the thickest and thinnest periods of DCT, is underway to validate the findings in this study with more animals from multiple herds and for subsequent genomic analysis. Long-term, genomic markers related to DCT will be evaluated for use in genetic selection to reduce lameness.

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LITERATURE CITED

Archer, S., N. Bell, and J. Huxley. 2010. Lameness in UK dairy cows: a review of the current status. In Practice. 32:492–504. doi:10.1136/inp.c6672

Barker, Z.E., J.R. Amory, J.L. Wright, S.A. Mason, R.W. Blowey, and L.E. Green. 2009. Risk factors for increased rates of sole ulcers, white line disease, and digital dermatitis in dairy cattle from twenty-seven farms in England and Wales. J. Dairy Sci. 92:1971–1978. doi:10.3168/jds.2012–6017

Bergsten, C., A. Brizzi, C.K.W. Mülling, and K. Nordlund. 2007. Genetic selection and conformation. In: Greenough, P., editor, Bovine laminitis and lameness: a hands-on approach. Edinburgh (UK): Elsevier. p. 141–154. doi:10.1016/B978-0-7020-2780-2.50016-1

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. doi:10.3168/jds.2007-0076

Bicalho, R.C., V.S. Machado, and L.S. Caixeta. 2009. 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. J. Dairy Sci. 92:3175–3184. doi:10.3168/jds.2008-1827

Bicalho, R.C., and G. Oikonomou. 2013. Control and prevention of lameness associated with claw lesions in dairy cows. Livest. Sci. 156:96–105. doi:10.1016/j.livsci.2013.06.007

Bludau, M.J., A. Maeschli, F. Leiber, A. Steiner, and P. Klocke. 2014. Mastitis in dairy heifers: prevalence and risk factors. Vet. J. 202:566–572. doi:10.1016/j.tvjl.2014.09.021

Cha, E., J.A. Hertl, D. Bar, and Y.T. Gröhn. 2010. The cost of different types of lameness in dairy cows calculated by dynamic programming. Pre. Vet. Med. 97:1–8. doi:10.1016/j.prevetmed.2010.07.011

Coffey, M.P., J. Hickey, and S. Brotherstone. 2006. Genetic aspects of growth of Holstein-Friesian dairy cows from birth to maturity. J. Dairy Sci. 89:322–329. doi:10.3168/jds.S0022-0302(06)72097-5

Cook, N.B., and K.V. Nordlund. 2009. The influence of the environment on dairy cow behavior, claw health and herd lameness dynamics. Vet. J. 179:360–369. doi:10.1016/j.tvjl.2007.09.016

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. doi:10.3168/jds.S0022-0302(89)79081-0

Foditsch, C., G. Oikonomou, V.S. Machado, M.L. Bicalho, E.K. Ganda, S F. Lima, R. Rossi, B.L. Ribeiro, A. Kussler, and R.C. Bicalho. 2016. Lameness prevalence and risk factors in large dairy farms in Upstate New York. Model development for the prediction of claw horn disruption lesions. PLoS One. 11:e0146718. doi:10.1371/journal.pone.0146718

Humer, E., A. Khol-Parisini, B.U. Metzler-Zebeli, L. Gruber, and Q. Zebeli. 2016. Alterations of the lipid metabolome in dairy cows experiencing excessive lipolysis early postpartum. PLoS One. 11:e0158633. doi:10.1371/journal.pone.0158633

Machado, V.S., L.S. Caixeta, and R.C. Bicalho. 2011. Use of data collected at cessation of lactation to predict incidence of sole ulcers and white line disease during the subsequent lactation in dairy cows. Am. J. Vet. Res. 72:1338–1343. doi:10.2460/ajvr.72.10.1338

Machado, V.S., L.S. Caixeta, J.A.A. McArt, and R.C. Bicalho. 2010. The effect of claw horn disruption lesions and body condition score at dry-off on survivability, reproductive performance, and milk production in the subsequent lactation. J. Dairy Sci. 93:4071–4078. doi:10.3168/jds.2010–3177

Mahen, P.J., H.J. Williams, R.F. Smith, and D. Grove-White. 2018. Effect of blood ionised calcium concentration at calving on fertility outcomes in dairy cattle. Vet. Rec. Published Online First: 11 July 2018. doi:10.1136/vr.104932

Markusfeld, O. 1987. Periparturient traits in seven high dairy herds. Incidence rates, association with parity, and interrelationships among traits. J. Dairy Sci. 70:158–166. doi:10.3168/jds.S0022-0302(87)79990–1

Mülling, C.K.W., and P.R. Greenough. 2006. Applied physiopathology of the foot. In: XXIV World Buiatrics Congress, Nice, France. Paris (France): World Association for Buiatrics. Available from http://www.ivis.org/proceedings/wbc/wbc2006/mulling.pdf?LA=1

Murray, R.D., D.Y. Downham, M.J. Clarkson, W.B. Faull, J.W. Hughes, F.J. Manson, J.B. Merritt, W.B. Russell, J.E. Sutherst, and W.R. Ward. 1996. Epidemiology of lameness in dairy cattle: description and analysis of foot lesions. Vet. Rec. 138:586–591. doi:10.1136/vr.138.24.586

Newsome, R.F., M.J. Green, N.J. Bell, N.J. Bollard, C.S. Mason, H.R. Whay, and J.N. Huxley. 2017. A prospective cohort study of digital cushion and corium thickness. Part 1: associations with body condition, lesion incidence, and proximity to calving. J. Dairy Sci. 100:4745–4758. doi:10.3168/jds.2016–12012

Newsome, R., M.J. Green, N.J. Bell, M.G.G. Chagunda, C.S. Mason, C.S. Rutland, C.J. Sturrock, H.R. Whay, and J.N. Huxley. 2016. Linking bone development on the caudal aspect of the distal phalanx with lameness during life. J. Dairy Sci. 99:4512–4525. doi:10.3168/jds.2015–10202

Nuss, K., C. Sauter-Louis, and B. Sigmund. 2011. Measurements of forelimb claw dimensions in cows using a standardised sole thickness: a post-mortem study. Vet. J. 190:84–89. doi:10.1016/j.tvjl.2010.10.002

Oikonomou, G., N.B. Cook, and R.C. Bicalho. 2013. Sire predicted transmitting ability for conformation and yield traits and previous lactation incidence of foot lesions as risk factors for the incidence of foot lesions in Holstein cows. J. Dairy Sci. 96:3713–3722. doi:10.3168/jds.2012–6308

Räber, M., Ch.J. Lischer, H. Geyer, and P. Ossent. 2004. The bovine digital cushion–a descriptive anatomical study. Vet. J. 167:258–264. doi:10.1016/S1090-0233(03)00053-4

Räber, M., M.R. Scheeder, P. Ossent, C.h.J. 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. doi:10.1016/j.tvjl.2005.03.009

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. doi:10.3168/jds.S0022-0302(01)74581-X

Ray, D.E., T.J. Halbach, and D.V. Armstrong. 1992. Season and lactation number effects on milk production and reproduction of dairy cattle in Arizona. J. Dairy Sci. 75:2976–2983. doi:10.3168/jds.S0022-0302(92)78061–8

Shearer, J.K., and S.R. Van Amstel. 2017. Pathogenesis and treatment of sole ulcers and white line disease. Vet. Clin. Food Anim. 33:283–300. doi:10.1016/j.cvfa.2017.03.0031

Shearer, J.K., S.R. Van Amstel, and B.W. Brodersen. 2012. Clinical diagnosis of foot and leg lameness in cattle. Vet. Clin. Food Anim. 28:535–556. doi:10.1016/j.cvfa.2012.07.003

Solano, L., H.W. Barkema, S. Mason, E.A. Pajor, S.J. LeBlanc, and K. Orsel. 2016. Prevalence and distribution of foot lesions in dairy cattle in Alberta, Canada. J. Dairy Sci. 99:6828–6841. doi:10.3168/jds.2016–10941

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. doi:10.1016/S0093-691X(97)00098-8

Tarlton, J.F., D.E. Holah, K.M. Evans, S. Jones, G.R. Pearson, and A.J.F. Webster. 2002. Biomechanical and histopathological changes in the support structures of bovine hooves around the time of first calving. Vet. J. 163:196–204. doi:10.1053/tvjl.2001.0651

Toussaint Raven, E. 1989. Cattle footcare and claw trimming. Ipswich (UK): Farming Press.

Van der Tol, P.P., J.H. Metz, E.N. Noordhuizen-Stassen, W. Back, C.R. Braam, and W.A. Weijs. 2002. The pressure distribution under the bovine claw during square standing on a flat substrate. J. Dairy Sci. 85:1476–1481. doi:10.3168/jds.S0022-0302(02)74216-1

Van der Tol, P.P.J., J.H.M. Metz, E.N. Noordhuizen-Stassen, W. Back, C.R. Braam, and W.A. Weijs. 2003. The vertical ground reaction force and the pressure distribution on the claws of dairy cows while walking on a flat substrate. J. Dairy Sci. 86:2875–2883. doi:10.3168/jds.S0022-0302(03)73884-3

Vergara, C.F., D. Döpfer, N.B. Cook, K.V. Nordlund, J.A.A. McArt, D.V. Nydam, and G.R. Oetzel. 2014. Risk factors for postpartum problems in dairy cows: explanatory and predictive modeling. J. Dairy Sci. 97:4127–4140. doi:10.3168/jds.2012–6440

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. doi:10.1016/j.tvjl.2006.10.006

Warnick, L.D., D. Janssen, C.L. Guard, and Y.T. Gröhn. 2001. The effect of lameness on milk production in dairy cows. J. Dairy Sci. 84:1988–1997. doi:10.3168/jds.S0022-0302(01)74642-5

Wathes, D.C., Z. Cheng, N. Bourne, V.J. Taylor, M.P. Coffey, and S. Brotherstone. 2007. Differences between primiparous and multiparous dairy cows in the inter-relationships between metabolic traits, milk yield and body condition score in the periparturient period. Domest. Anim. Endocrinol. 33:203–225. doi:10.1016/j.domaniend.2006.05.004