Interpretive summary: Digital dermatitis and infrared thermographic imaging

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We investigated the association between bovine digital dermatitis lesions and the interdigital skin temperature measured by infrared thermography. All clinical stages of digital dermatitis were associated with increased foot skin temperature. Feet with active lesions were recorded having higher mean interdigital skin temperature, compared to feet with chronic, inactive digital dermatitis lesions and non-affected feet. This finding led to the development and validation of predictive models that use interdigital skin temperature readings, among other variables, as input in order to distinguish between feet affected with active digital dermatitis and non-affected feet or feet bearing chronic digital dermatitis lesions.

DIGITAL DERMATITIS AND INFRARED THERMOGRAPHIC IMAGING

A study on the use of thermal imaging as a diagnostic tool for the detection of digital dermatitis in dairy cattle

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ABSTRACT

Our aims were to (i) determine how interdigital skin temperature (IST), measured using infrared thermography, was associated with different stages of digital dermatitis (DD) lesions and (ii) develop and validate models that can use IST measurements to identify cows with an active DD lesion. Between March 2019 and March 2020, infrared thermographic images of hind feet were taken from 2,334 Holstein cows across four farms. We recorded the maximum temperature reading from infrared thermographic images of the interdigital skin between the heel bulbs on the hind feet. Pregnant animals were enrolled approximately one to two months pre-calving, re-assessed a week after calving and finally at approximately 50-100 days postpartum. At these time-points, IST and the clinical stage of DD (M-stage scoring system: M1-M4.1) were recorded in addition to other data such as the ambient environmental temperature, height, body condition score, parity and the presence of other foot lesions. A mixed effect linear regression model with IST as the dependent variable was fitted. Interdigital skin temperature was associated with DD lesions; comparing to healthy feet IST was highest in feet with M2 lesions followed by M1 and M4.1 lesions. Subsequently, the capacity of IST measurements to detect the presence or absence of an active DD lesion (M1, M2, or M4.1) was explored by fitting logistic regression models which were tested using ten-fold validation. A mixed effect logistic regression model with the presence of active DD as the dependent variable was fitted first. The average area under the curve (**AUC**) for this model was 0.80 when its ability to detect presence of active DD was tested on ten percent of the data that were not used for the model's training; an average sensitivity of 0.77 and an average specificity of 0.67 was achieved. This model was then restricted so that only explanatory variables which could be practically recorded in a non-research, external setting were included. Validation of this model demonstrated an average AUC of 0.78 and a sensitivity of 0.88 and a specificity of 0.66 for one of the time-points (pre-calving). Lower sensitivity and specificity were achieved for the other two time-points. Our study adds further evidence to the relationship between DD and foot skin temperature using a large dataset with multiple measurements per animal. Additionally, we highlight the potential for infrared thermography to be utilised for routine on-farm diagnosis of active DD lesions.

Key words digital dermatitis, lameness, infrared thermography, M scoring

INTRODUCTION

Bovine Digital Dermatitis (**DD**) is a major cause of lameness in dairy cattle and is a disease of increasing economic and welfare importance (Evans et al., 2016). Digital dermatitis lesions are most frequently found on the plantar skin of the hind feet bordering the interdigital space. Lesion appearance can vary but lesions usually appear as circumscribed, erosive to papillomatous lesions surrounded by a ridge of hyperkeratotic skin bearing hypertrophied hairs (Read and Walker, 1998). Digital dermatitis is a multifactorial infectious disease and many bacterial species have been isolated from lesions; Spirochaetes, specifically *Treponema* species, have been demonstrated to play a key role in disease aetiopathogenesis (Evans et al., 2016).

Accurate diagnosis of DD requires restraint of the cow in a hoof trimming chute to lift and examine each foot. This process is labour intensive and limits the number of cows which can be examined in a short period of time. Therefore, various diagnostic approaches to identify affected hind feet of cows in the milking parlour have been developed (Yang and Laven, 2019). Although inspecting hind feet in the parlour significantly improves the efficiency of DD diagnosis, early-stage or small lesions can be missed. Furthermore, as gross contamination of the distal limb can obscure DD lesions, the requirement to wash cows' feet can potentially compromise udder hygiene (Oliveira et al., 2017).

Infrared thermography has been widely used in veterinary medicine in order to detect temperature changes caused by inflammatory conditions including digital dermatitis and other lameness causing foot lesions (Wood et al., 2015). Measuring the maximum temperature of the plantar aspect of the hind feet and using a maximum temperature cut-off of 27 ℃, Stokes et al. (2012) achieved an 80 % sensitivity and 73% specificity in diagnosing the presence of any foot lesion. An increase in the temperature of the coronary band associated with the presence of DD lesions was described by Alsaaod et al. (2014). Using the difference in maximum temperature of the coronary band between front and hind feet and a cut-off in temperature difference of 0.99 °C a combination of 89.1% sensitivity and 66.6% specificity was achieved.

Digital dermatitis lesions can be classified according to the M-stage scoring system which is based on the gross appearance of the lesion (Berry et al., 2012). These stages can be broadly divided into active lesions (M1, M2 and M4.1) and healing or chronic lesions (M3 and M4 respectively) (Zinicola et al., 2015). Active lesions are more likely to be painful whereas healing and chronic lesions are painless, although they can transition back to an active state (Palmer and O'Connell, 2015; Biemans et al., 2018). Given that active lesions are more painful and possibly more likely to be a source of infection (Beninger et al., 2018), they are the main focus of routine diagnostic and treatment efforts. As the M-stages differ in size, severity and histological profile, it is reasonable to assume that such differences may be reflected on the local skin temperature.

The objectives of our study were to (i) determine how interdigital skin temperature (**IST**), measured using infrared thermography, was associated with different stages of DD lesions and (ii) develop and validate models that can use IST to identify cows with an active DD lesion.

MATERIALS AND METHODS

Farm selection

The study was approved by the University of Liverpool Research Ethics Committee (VREC466ab, VREC269a). Data collection was conducted alongside a project on the aetiopathogenesis and genomic architecture of resistance to claw horn disruption lesions which enrolled 2,353 Holstein cows across four farms in the North of England and Wales. Farm selection for this project was based on proximity to the University of Liverpool Leahurst Campus and on farmers' willingness to collaborate.

Data collection

All purebred Holstein cows with an expected calving date between March and December 2019 were eligible for enrolment. Cows and nulliparous heifers were enrolled approximately 60 to 30 days before their expected calving ("pre-calving"). Data were collected again at approximately one week ("calving") and 50-100 days ("early lactation") postpartum.

At each assessment time-point ("pre-calving, "calving" and "early lactation"), thermal images of hind feet were taken and foot lesions from all limbs were recorded and graded according to severity. All feet were lifted and examined by a qualified veterinarian. DD lesions were scored using the M-stage scoring system. All other lesions were recorded based on the ICAR claw health atlas (Egger-Danner et al., 2014). Mobility score was recorded as described by the UK Agricultural and Horticultural Development Board (Reader et al., 2011). Body Condition Score (**BCS**) was assessed using a 1-5 scale with 0.25 increments (Ferguson et al., 1994). The sacral height was recorded to the nearest 5 cm. Ambient environmental temperature was recorded at the start and end of each data recording session. Data collection was the same at all three time-points except at the "calving" time-point on one farm (farm three) during which only hind feet were inspected for lesions. All cows had routine foot-trimming conducted by farm or research staff at (or close to) the "pre-calving" and "early lactation" time-points.

Thermal Imaging

Images were taken of the plantar aspect of the foot from a 30 cm approximate distance using a thermal camera (FLIR E8-XT, FLIR Systems, Oregon, US). Feet were not washed prior to thermal imaging and the skin between the heel bulbs was not cleaned. Sole temperature was also recorded for the purposes of the main study; for this reason manure was quickly wiped off in cases where the sole was not visible. Emissivity value was set at 0.95. Using the FLIR Tools software and the maximum temperature search tool, a circular search area was chosen between the heel and the accessory bulbs and the maximum IST was recorded (Figure 1).

Statistical analysis

All data were recorded in Microsoft Access and analysed using R (R Development Core Team 3.6., 2019). Records of feet at each assessment time-point were only included in subsequent analysis if IST had been recorded and if the hind foot had been inspected for lesions (2,349 /2,353 cows). Additionally, records were excluded at each time-point if other data were missing (e.g. BCS); consequently records from 2,334 cows were retained for statistical analysis. The ambient temperature recorded at the start and end of each data collection session was averaged. If one of these measurements was missing then the single measurement was used instead (1,111/12,221 records); if both were missing (282/12,221 records) then the mean temperature recorded that day was used; finally, if no ambient temperature was recorded on that day then the mean of the farm at that assessment point was used. Parity was considered as a two-level variable which identified primiparous and multiparous animals. Farm and assessment time-point were treated as four-and three-level categorical variables respectively. BCS was binned into three categories: ≤2.5, 2.75-3.25 and ≥3.5; similarly, sacral height was binned as: <145cm, 145-150cm and >150cm. Mobility score (0-3) was kept as a four-level categorical variable. Foot lesions on hind feet other than DD were summarised into a single binary variable to indicate the presence or absence of a foot lesion other DD. Finally, foot was included as a two-level variable (i.e. left-hind or right-hind).

(i) Factors affecting IST

Univariable linear regression analysis was conducted using IST as the dependent variable. Ambient temperature, farm, assessment time-point, parity, BCS, height, mobility score, foot, DD stage (healthy, M1-M4.1) and presence of non-DD foot lesions were analysed to assess their association with IST.

All explanatory variables with $P < 0.1$ in the univariable analysis were fitted into a multivariable model using the lme4 package (Bates et al., 2015). An automated backwards stepwise selection process was performed using the MASS package (Venables and Ripley, 1996), whereby the Akaike information criterion (AIC) was assessed following the removal of each covariate from the model. To account for the repeated measures within each cow, the cow identity was included as a random effect in the model. Once the most parsimonious model had been determined, the covariates were assessed for multicollinearity and all two-way interactions were assessed. Significant interaction terms (Wald chi-squared test < 0.05) were plotted to assess their biological plausibility and relevance. Residual errors were plotted to check for normality and homoscedasticity. The estimated marginal means for IST, as predicted by the model, were calculated for each stage of DD using the emmeans package (Lenth et al., 2020). Pairwise comparisons were made using Tukey's Honestly Significant Difference test.

(ii) Detection of active DD lesions using IST measurements

The aim of this analysis was to determine the capacity of IST measurements to identify cows with active DD lesions. Univariable analysis included ambient temperature, IST, farm, assessment time-point, parity, BCS, height, mobility score, foot, and the presence of non-DD foot lesions. Interdigital skin temperature and ambient temperature were combined into a composite index. This index (adjusted IST) was calculated as the difference between the recorded IST and the predicted from the regression of IST on ambient temperature IST, centred around the mean ambient temperature recorded during the study. The formula used was:

Adjusted IST= IST – (a - (b*(Ambient Temperature – Study Mean Ambient Temperature))). Values a (17.52) and b (0.49) are derived from the multivariable linear regression model describing the relationship between IST and Ambient temperature. The Study Mean Ambient Temperature refers to the overall across farms average of all Mean Ambient Temperatures recorded and is equal to 15.28℃.

The multivariable model was constructed in a similar way as described above using the same R packages. All significant explanatory variables from univariable analysis were fitted and then removed in an automated stepwise process based on the resulting AIC of the model. Cow was included in the model as a random effect. Covariates were assessed for multicollinearity and all two-way interactions were assessed. This mixed effect model failed to consistently converge when potential interactions were included and therefore no interaction terms were included in the final model. In order to test the classification capability of this model, validation on 10% of the dataset was performed ten times. The dataset was randomly partitioned into a training dataset containing 90% of the animals and a testing dataset with the remaining 10%. The model was fitted on the training dataset and used to plot an ROC. The cutpointr package (Thiele, 2019) was used to determine the optimal cut-off of predicted probability to detect the presence/absence of an active DD lesion for a maximum sensitivity whilst retaining a minimum specificity of 0.65. The model was then used to detect the presence of an active DD lesion on the testing dataset using the optimal cut-off to dichotomise results and calculate a confusion matrix. This process was repeated ten times and the results were averaged. The same model and validation process were fitted again but with the aim to detect only the presence of M2 stage DD.

A simpler, more practical model (“farm friendly”) was then considered that could theoretically be used to identify presence of active of DD in an external population from different farms. Specifically, assessment time-point, farm and the random cow effect were removed from this “farm friendly” model as they were specific to our study population. Furthermore, data that would be difficult to record would limit the practical application of the model and therefore the presence of other foot lesions was also excluded. As the random effect of cow was not retained in this model we fitted three models separately at each time-point to avoid the effects of clustering.

RESULTS

A total of 2,334 cows were included in this project, providing a total of 12,221 hind feet with lesion records and thermal images for analysis. Descriptive data for the study population are summarised in Table 1.

(i) Association of IST with DD lesions

The final linear mixed effect model with IST as the dependent variable included ambient temperature, farm, assessment time-point, parity, BCS, height, mobility score, foot, and presence of non-DD foot lesions as fixed effects, and cow as a random effect. Results from this model are presented in Table 2. The adjusted means for IST for each stage of DD are presented in Table 3 together with all pairwise comparisons between stages. All DD stages resulted in a statistically significantly higher IST compared to feet with no DD lesions; M2 lesions were associated with the highest IST. The ambient temperature alone explained a substantial proportion of the variation in IST (R^2: 0.26). In the final model, the fixed effects component explained 42.04% of the variation in IST; 17.10% was explained by the random effect (cow).

(ii) Identification of active DD lesions based on IST

The results of the mixed effect logistic regression model with presence of active DD as the dependant variable are presented in Table 4. The final model included adjusted IST, farm, assessment time-point, parity, BCS, height, and presence of non-DD foot lesions as fixed effects and cow as a random effect. The AUC for this model was 0.97 when using 90% of the data in the training and was 0.80 when the model was fitted on the 10% of the data that were not used for model training. The ten-fold validation process produced an average sensitivity and specificity (achieved when the model predictions were applied on the 10% of the data that were not used to train the model) of 0.77 and 0.67 respectively (Table 5). Univariable analysis indicated that adjusted IST explained a substantial proportion of the variation in the probability of an active DD lesion being present (pseudo-R squared: 0.229). The relationship between adjusted IST and the model predicted probability of an active DD lesion being present is displayed in Figure 2.

The mixed-effects model detecting only the presence of M2 stages of DD achieved and average AUC of 0.86 (when fitted on the 10% of the data not used for the training of the model). The ten-fold validation process produced a combination of 83.11% average sensitivity and 70.64% average specificity.

The more practical ("farm friendly") logistic regression model, with active DD as the dependant variable, included adjusted IST, height, BCS and parity as the only explanatory variables. Separate models were fitted for each assessment time-point and all explanatory variables remained significant ($P < 0.05$) in the model in each instance. The average AUC was 0.78 for this model across all time-points and following a ten-fold validation. The average sensitivities and specificities achieved after ten-fold validation for this model at each assessment time-point are shown in Table 5.

DISCUSSION

We show here that DD lesions are strongly associated with IST (as measured with infrared thermography). M2 stage lesions were associated with the highest IST; all DD stages were associated with a statistically significant increase in IST comparing to feet with no DD lesions.

The mixed effect logistic regression model was effective in identifying the presence of active DD with an AUC of 0.80; the more practical, “farm friendly”, model still achieved an AUC of 0.78. When tested on 10% of the data the mixed effect model achieved an average sensitivity of 76.94% and an average specificity of 67.04%. The “farm friendly” model tested in the same way on the “pre-calving” data achieved an average sensitivity of 88.14% and an average specificity of 65.83%. However, sensitivity and specificity was lower at the other two time-points.

To the best of our knowledge, this is the first study to investigate differences in IST between different stages of DD lesions, utilising a large dataset. As expected, M2 stage lesions had the highest mean IST reading; these lesions cover a large area of the foot and are associated with severe inflammatory signs. M1 stage lesions also resulted in higher IT compared to M0 and M4 lesions. M3 lesions are considered to be healing lesions (Biemans et al., 2018; Döpfer et al., 2012); our data show that there were no significant IST differences between them and M1 lesions (which are considered early-stage, active lesions).

Foot skin temperature measurements have been previously found to be affected by many factors associated with the cows’ production stage and health and with environmental conditions (Alsaaod et al., 2015). Ambient temperature explained 10% of the variation in IST measurements in a study by Stokes et al. (2012). In our study, 25% of the variation in IST measurements was explained by ambient temperature. This may be due to the fact that our data collection lasted approximately 12 months, with the lowest ambient temperature being 1.6 °C and the highest 30.8 °C. The difference in mean IST between right and left feet could be explained by the positioning and orientation of the chutes in different farms. In farm three, for example, where the largest amount of data was collected, the right side of the chute was always under shade while the same was not the case for the left side. Primiparous animals in farms two and three had higher IST readings than multiparous animals; similar findings have been reported previously (Nikkhah et al., 2005).

When the mixed effect model identifying the presence of active DD lesions was validated on 10% of the data, the average achieved sensitivity was 76.94% and the average achieved specificity was 67.04%. The practical, “farm friendly” model produced similar results when it was validated on data from the “pre-calving” time-point (average sensitivity of 88.14%, average specificity of 65.83%). A threshold for minimum specificity of 65% while aiming for maximum sensitivity was set in this analysis because, when attempting to maximise the sum of sensitivity and specificity, the produced cut-off would result in high specificity values (>85%) but poor sensitivity values (<50%). Decreased specificity when aiming for better sensitivity was associated with the fact that M1 lesions had similar mean IST to M3 lesions. In addition, other lesions (especially severe sole ulcers, white line disease and toe ulcers) were also found to substantially increase the IST. Investigating every different foot lesion separately was beyond the scope of the present study but could be the aim of future work. The predictive capabilities of our models appear to be better than models developed previously that used infrared thermography to predict oestrus (Talukder et al., 2014) but worse than models developed to use infrared thermography for identification of subclinical mastitis (Polat et al., 2010). Given the accuracy of our models in detecting active DD, even in M1 and M4.1 stages, an automated system recording the IST of each foot during milking could potentially be developed and utilised for routine in-parlour diagnosis of DD; such a system could be particularly useful in large dairy herds. Utilising such a setup, daily measurements of IST and machine learning approaches, sensitivity and specificity could improve further. Similar approaches are being taken for the automatic detection of bovine mastitis (Xudong et al., 2020). Utilising different cut-off values for identification of presence of active DD lesions farmers can opt for increased sensitivity or specificity. The former will lead to early identification and treatment of most DD lesions but will also mean that a number of cows will be flagged without actually being affected with DD.

Our study does have some limitations that need to be taken into consideration. The farms used here had a relatively low prevalence of active DD lesions; including farms with higher prevalence of active DD lesions would have improved our study’s external validity. Thermographic images were obtained from lifted feet and this cannot be the case if an automatic system for in parlour detection is to be developed. The area we targeted can be targeted without lifting the feet so we could argue that we could obtain similar results obtaining thermographic images in the parlour; however, we cannot be certain that our models’ performance would remain the same in that case.

CONCLUSION

Our study shows that infrared thermography could be utilized for the diagnosis of active cases of DD. Models detecting the presence of DD had acceptable sensitivity and specificity and may be implemented in routine monitoring of foot health in commercial dairy farms. Further studies addressing some of our study’s limitations are warranted before such systems become commercially available.

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Table 1. Descriptive statistics of the studied population. Lameness prevalence is defined as a mobility score of 2 or 3

	Farm			
	1	2	3	4
Enrolled multiparous animals	96	187	1100	360
Enrolled primiparous animals	36	52	450	72
Total Enrolled	132	239	1550	432
Reassessed at “calving” time-point	124	214	1475	404
Reassessed at “early lactation” time-point	124	212	1393	396
Animals with IST[1] measurements (“pre-calving”)	111	193	1406	407
Animals with IST[1] measurements (“calving”)	123	198	1403	380
Animals with IST[1] measurements (“early lactation”)	116	203	1297	378
BCS[3]	3.25 (3-3.5)	3.25 (3-3.5)	3.25 (3-3.5)	3.25 (3-3.5)
Height[4] (cm)	150 (145-155)	150 (145-155)	150 (145-155)	150 (145-155)
Lameness prevalence (“pre-calving”)	2.73%	8.29%	7.55%	5.21%
Lameness prevalence (“calving”)	11.67%	9.14%	8.78%	8.18%
Lameness prevalence (“early lactation”)	18.58%	11.39%	7.13%	5.12%
Feet with active DD[2] lesions / Total feet evaluated (“pre-calving”)	5%	4.14%	2.83%	1.97%
Feet with active DD[2] lesions / Total feet evaluated (“calving”)	5.42%	4.31%	4.89%	1.85%
Feet with active DD[2] lesions / Total feet evaluated (“early lactation”)	3.98%	0.25%	3.80%	1.62%

[1] IST: Interdigital skin temperature

[2] DD: Digital dermatitis

[3-4] Median, 25th and 75th percentile

Table 2. Results from the mixed effect multivariable linear regression model examining factors affecting interdigital skin temperature

Explanatory Variables	Levels	Estimate	SE[6]	*P*-value
Intercept[1]		21.45	0.53	<0.001
BCS[2]	2	-0.29	0.17	0.100
	3	-0.05	0.19	0.801
Mean Ambient Temperature	Continuous	0.49	0.01	<0.001
Height[3]	2	0.30	0.16	0.053
	3	0.01	0.18	0.936
Foot	Back right	-0.20	0.06	<0.001
Mobility	1	0.25	0.08	0.001
	2	1.32	0.14	<0.001
	3	1.68	0.41	<0.001
Parity[4]	2	-0.55	0.49	0.260
Digital Dermatitis	M1	1.67	0.31	<0.001
	M2	5.10	0.24	<0.001
	M3	0.81	0.24	0.001
	M4	0.37	0.11	0.001
	M4.1	2.62	0.36	<0.001
Other lesion[5]	1	0.15	0.07	0.022
Farm	2	-3.24	0.58	<0.001
	3	-2.75	0.46	<0.001
	4	-0.94	0.54	0.080
Time-point	Calving	-2.60	0.32	<0.001
	Early Lactation	-1.79	0.33	<0.001
Interactions				
Parity2xFarm2		-1.60	0.61	0.009
Parity2xFarm3		-2.85	0.49	<0.001
Parity2xFarm4		-1.33	0.57	0.019
Farm2xFresh		1.37	0.37	0.000
Farm3xFresh		1.68	0.30	<0.001
Farm4xFresh		0.46	0.33	0.169
Farm2xEarly lactation		0.60	0.37	0.111
Farm3xEarly lactation		-0.38	0.31	0.221
Farm4xEarly lactation		0.73	0.34	0.031
Parity2xFresh		2.40	0.16	<0.001
Parity2xEarly lactation		2.28	0.17	<0.001

[1] The Intercept automatically includes the first level of all factors fitted

[2] BCS: 1 = <2.5, 2 = 2.75-3.25, 3 = ≥3.5

[3] Height: 1 = <145cm, 2 = 145-150cm, 3 = >150cm

[4] Parity: 1 = Primiparous, 2 = Multiparous

[5] Other lesion: 0 = Absence, 1 = Presence of other foot lesion

SE: standard error

Table 3. Estimated marginal means (EMM) for each stage of digital dermatitis (DD) and pairwise comparison of means using Tukey's honestly significant difference test

Digital Dermatitis Group	EMM *	SE	
M0	26.60	0.15	
M1	28.30	0.34	
M2	31.70	0.28	
M3	27.40	0.28	
M4	27.00	0.18	
M4.1	29.30	0.38	
Contrast	Estimate*	SE	*P*-value
0 - 1	-1.67	0.31	<0.001
0 - 2	-5.10	0.24	<0.001
0 - 3	-0.81	0.24	0.011
0 - 4	-0.37	0.11	0.010
0 - 5	-2.62	0.36	<0.001
1 - 2	-3.43	0.38	<0.001
1 - 3	0.86	0.38	0.209
1 - 4	1.30	0.31	0.001
1 - 5	-0.96	0.46	0.304
2 - 3	4.29	0.33	<0.001
2 - 4	4.73	0.26	<0.001
2 - 5	2.48	0.42	<0.001
3 - 4	0.44	0.25	0.499
3 - 5	-1.81	0.42	<0.001
4 - 5	-2.25	0.36	<0.001

*Estimated marginal means and estimates of comparison are measured in ℃

For the contrast of Digital Dermatitis (DD) stages, they are represented by the factor levels: M0=0, M1=1, M2=2, M3=3, M4=4 and M4.1=5

Table 4. Results from mixed effect logistic regression model with active digital dermatitis as the dependant variable

Fixed effects:	Levels	Estimate	SE[6]	P value
Intercept[1]		-9.060	0.699	<0.001
Adjusted IST[2]	Continuous	0.317	0.019	<0.001
Height[3]	2	0.538	0.347	0.121
	3	0.566	0.380	0.136
BCS[4]	2	0.137	0.331	0.679
	3	-0.351	0.364	0.335
Farm	2	0.239	0.419	0.568
	3	0.860	0.324	0.008
	4	-0.716	0.391	0.067
Other lesion[5]	1	0.629	0.144	<0.001
Parity[6]	2	-0.095	0.195	0.626
Stage	Fresh	0.371	0.155	0.017
	Early lactation	0.005	0.185	0.979
Random Effect		Variance	Std. Dev.	
Cow ID		3.301	1.817	

[1] The Intercept automatically includes the first level of all factors fitted

[2] adjusted IST: The estimate for this continuous variable refers to the increase in predicted probability for every 1°C increase of adjusted interdigital skin temperature.

[2] Height: 1 = <145cm, 2 = 145-150cm, 3 = >150cm

[3] BCS: 1 = <2.5, 2 = 2.75-3.25, 3 = ≥3.5

[4] Other lesion: 0 = Absence, 1 = Presence of other foot lesion

[5] Parity: 1 = Primiparous, 2 = Multiparous

[6] SE: standard error

Table 5 Mean model sensitivity and specificity from ten-fold validation for logistic regression models. The mixed effect models assessed all stages simultaneously

	"Farm-friendly" model			Mixed effect model[1]	Mixed effect model 2[2]
	Pre-calving	Calving	Early-lactation	All stages	All stages
Mean Sensitivity	88.14%	69.66%	69.07%	76.94%	83.11%
Mean Specificity	65.83%	65.98%	67.42%	67.04%	70.64%

[1] Refers to the mixed effect logistic regression model with stages M1, M2 and M4.1 treated as active stages

[2] Refers to the mixed effect logistic regression model with only M2 treated as active stage

Figure 1. Measurement of interdigital skin temperature. Circular tool used to measure the maximum interdigital skin temperature (Bottom red mark). This image demonstrates that as long as the tool stays between the heel and accessory bulbs, the area covered does not affect the final reading.

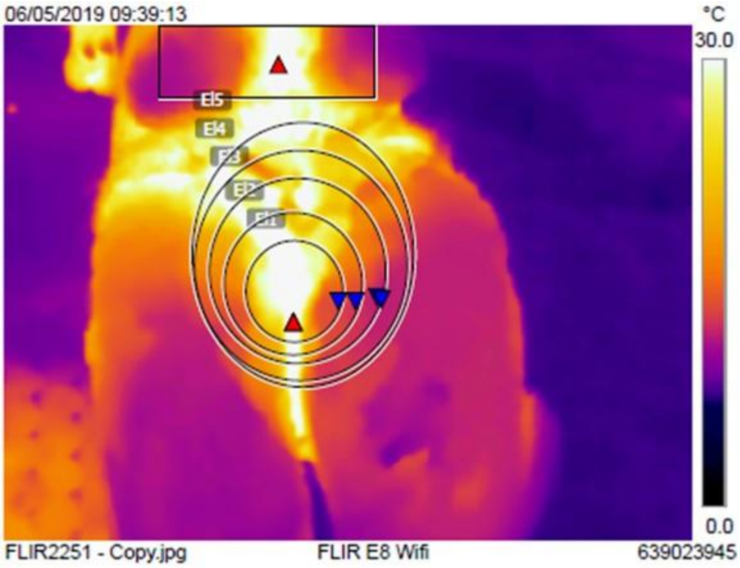

Figure 2. Plotted predicted probability of presence of an active digital dermatitis lesion against adjusted interdigital skin temperature (IST) (results from the mixed effect logistic regression model). Points represent feet and are coloured based on their stage on the M scoring system (M0 to M4.1). The horizontal line represents a cut-off taken based on predicted probability. Feet with probability higher than the line are classified as active cases.