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The use of infrared thermography for detecting digital dermatitis in dairy cattle: what is the best measure of temperature and foot location to use?

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Abstract

Lameness in dairy cattle is a persistent problem, indicating pain caused by underlying disease states and is associated with reduced milk yields. Digital dermatitis is a common cause of lameness. Thermal imaging is a technique that may facilitate early detection of this disease and has the potential for use in automated detection systems. Previous studies with thermal imaging have imaged either the heels or the coronary band of the foot and typically only used the maximum temperature (Max) value as the outcome measure. This study investigated the utility of other statistical descriptors: 90^{th} percentile (90PCT), 95^{th} percentile (95PCT), standard deviation (SD) and coefficient of variation (CoV) and compared the utility of imaging the heel or coronary band. Images were collected from lame and healthy cows using a high-resolution thermal camera. Analyses were done at the cow and foot level. There were significant differences between lame and healthy feet detectable at the heels (95^{th} percentile: $P<0.05$; SD: $P<0.05$) and coronary band (SD: $P<0.05$). Within lame cows, 95PCT values were higher at the heel ($P<0.05$) and Max values were higher at the coronary band ($P<0.05$) in the lame foot compared to the healthy foot. ROC analysis showed an AUC value of 0.72 for Max temperature and 0.68 for 95PCT at the heels. It was concluded that maximum temperature is the most accurate measure, but other statistical descriptors of temperature can be used to detect lameness. These may be useful in certain contexts, such as where there is contamination. Differentiation of lame from healthy feet was most apparent when imaging the heels.

Key words: lameness, dairy cattle, thermal imaging, disease detection

Introduction

Lameness is one of the most common production diseases affecting modern dairy cows. It is recognised as causing pain (Whay et al., 1998) and is associated with reduction in milk yield (Green et al., 2002; Archer et al., 2010) and fertility (Hultgren et al., 2004). The incidence of lameness has been reported as varying between 21 and 69% in North America (Cook, 2003; Solano et al., 2015) and from 21 % to 37% in the United Kingdom, varying with the grazing and housing system used (Rutherford et al., 2009; Barker et al., 2010). In particular, digital dermatitis (DD) is currently one of the most prevalent infectious diseases associated with lameness, affecting around 70% of all UK dairy herds (Archer et al., 2010). Within-herd prevalence of digital dermatitis has been estimated as between 0 and 74% (Somers et al., 2005; Holzhauer et al., 2006; Solano et al., 2015; Jacobs et al., 2017).

Early detection of infectious conditions such as digital dermatitis facilitates prompt treatment, and is considered the best method of reducing the overall severity of the disease (Stokes et al., 2012; Alsaaod et al., 2014). Such timely detection and treatment of conditions leading to lameness will not only prevent progression of the condition (Leach et al 2012), but will reduce the level of the infective reservoir within the herd (Stokes et al., 2012). However, this requires that producers have a reliable method of detecting DD available to them, as well as the time and resources to provide appropriate treatment and care. Changes in locomotion or gait characteristics are often the first detectable signs of foot disease. Visual gait scoring methods have been developed to assess lameness (e.g. Manson and Leaver, 1988; Sprecher et al., 1997). However, despite the presence of these systems and other initiatives, prevalence remains high. For instance in the UK, a prevalence of 36.8% was reported in 2010 by Barker et al., which is comparable to the prevalence of 31.6% found in a recent study (Griffiths et al., 2018). Automated systems of lameness detection may be useful, so that the farmer does not need to set aside time to observe cows walking. There are automated systems assessing pressure and force of cows’ feet when walking or standing (e.g. Rajkondawar et al., 2006; Pastell et al., 2010; Maertens et al., 2011) and more recently, systems have been developed to detect the change in feeding behaviour and activity associated with lameness (e.g. Mazrier et al., 2006; Blackie et al., 2011; Beer et al., 2016). However, the use of more than one type of sensor has been suggested as a way of increasing the accuracy of detection of issues (Borchers et al., 2017). As well as some measure of change in activity, another independent variable such as a measure of infection, would improve detection rates.

In this regards, a non-invasive, accurate and cost-effective method of detecting inflammation or infection would be useful, particularly useful in the case of DD. The use of infrared thermography (IRT) has been suggested as a method of determining whether heat associated with inflammation or infection is present in the feet of cattle (Alsaaod and Büscher, 2012). Thermal imaging is a suitable device for use in animals as it is non-invasive and the camera is remote form the individual being assessed (Stewart et al., 2005). The body surface temperature of animals is influenced by air temperature, convection and radiation and by insulation but is determined also by the blood flow and metabolic rate of the underlying tissues. Thus, measurement of surface or skin temperature using IRT may detect changes in local blood flow due to infection and inflammation (Eddy et al, 2001). Infrared thermography captures the spatial temperature profile of a target area and produces a visual map or thermogram of the surface temperature of this area by utilising false colour scales to represent pre-defined temperatures. Infrared thermographic devices contain an array of sensors and algorithms that measure incoming radiation and convert the values into temperatures. Thus the thermogram contains as many temperature values as there are measurement sensors. Many imaging devices also report the highest temperature within the field of view on a viewing screen, but the presence of this background data in each thermogram opens up the opportunity of using this data in other ways to detect lameness.

Infrared thermography has been used previously to detect foot conditions associated with lameness in horses (Turner, 1991; Eddy et al., 2001) and changes in udder temperature associated with mastitis in dairy cows (Berry et al., 2003). Previous studies have also shown that thermal imaging or thermography can be used in cattle to differentiate between feet affected by lameness-causing lesions and healthy feet (Alsaaod and Büscher, 2012; Stokes et al., 2012; Alsaaod et al., 2014). Non-contact infra-red thermometry has shown similar results (Main et al., 2012; Wood et al., 2014). These studies have involved imaging two major parts of the feet, the coronary band (e.g. Nikkhah et al., 2005; Alsaaod and Büscher, 2012; Alsaaod et al., 2014) and the rear aspect of the hind feet above the heel bulbs (Main et al., 2012; Stokes et al., 2012). The majority of these studies used the maximum temperature detected in the target area as an indicator of the presence of lameness in the foot. However, it is possible that the presence of a lesion or an inflammatory condition might be more accurately detected by using other statistical descriptors of the data obtained from a spatial profile of surface temperatures in the target area.

The aim of this study was to determine whether statistical descriptors that summarise the temperature data other than the maximum temperature were more effective and accurate at distinguishing lame from non-lame cows. The statistical descriptors assessed were the mean, the 90th and 95th percentiles and the maximum temperatures. As the statistical spread of temperatures will also be affected, two measures of variation were assessed: the standard deviation and the coefficient of variation. The relative utility of imaging the heel or the coronary band areas was also investigated.

Materials and Methods

Animals, husbandry and management

This study was conducted using an experimental herd of 200 Holstein dairy cattle, based at Crichton Royal Farm, Dumfries, Scotland. The study methods were approved by Scotland's rural College's Animal Experiments Committee (Submission number: ED AC 45-2013) on 26th November, 2013. The herd was managed in two separate feeding and management systems as part of an experiment investigating the effects of genetic line (high genetic merit for milk yield vs. a control line) and management (indoor housing/bought in feeds vs. outdoor housing in summer/feedstuffs grown on the farm) on milk yield and health. Cows were removed from the herd following the fourth lactation and herd turnover was around 25% annually. Historically, digital dermatitis has been the most prevalent infectious condition causing lameness in the herd throughout the year, with a prevalence of 2-3%, and the prevalence of solar ulcers is 1% or less. The overall prevalence of lameness is 8% (Chagunda, 2012).

The indoor housing consisted of a large, well-ventilated barn with standard cubicle beds with at least one bed per cow and two passageways (one behind the feed trough and one between the two rows of cubicles). Passageways were wide enough for 2 cows to pass. All flooring was concrete and an automatic scraper ran down the passageways every hour. Water troughs were located at either end of the barn and were raised to ensure cows were not standing in slurry whilst drinking. All lactating cows were milked three times per day (approximately 6:00, 14:00 and 21:00h). In the spring (mid-March), the cows in the outdoor management group began to be grazed outdoors, initially in one time 'window' between milkings. By mid-April they were grazing all day, but were housed at night. Whilst indoors, all cows were fed on a total mixed ration which contained 1.8 - 12.0 MJ/kg DM. Three times a week, all cows were walked through a copper sulphate foot-bath as a preventative measure against infectious foot diseases. Remedial foot trimming was performed as necessary by the vet on cows identified as lame at any stage, but was performed routinely twice a year on the entire herd to maintain good hoof health.

Lameness scoring and foot examination

Cows were locomotion scored on a fortnightly basis by experienced technical staff. Any cows scoring above 3-4 on the lameness scale used (1-4 scale from sound to very lame, after Manson and Leaver, (1988), were noted, ready for veterinary inspection. Inter-observer reliability for this score is around 70% (e.g. Rutherford et al., 2009). Healthy cows with scores of 1 were also identified at this time. The vet (CM) visited the within 1-3 days of locomotion scoring to inspect and treat these cows.

Foot examination and image collection

Foot examination took place in a claw trimming crush and was carried out by an experienced veterinary surgeon (CM). All cows identified as lame were separated from their management groups and held as a group in a holding pen beside the crush. Control cows, with a locomotion score of 1, were also identified, observed again to confirm this score, and included in this group in the holding pen. One by one, each cow was inspected in the crush. Before any handling of the feet took place, images were taken of the front of the coronary band and the plantar aspect of the pastern joint (image taken from ground level of the area between the heel bulbs and the dew claws) of both rear feet. The feet were not cleaned with water or by any other method. Using only dirty feet not only makes results more applicable for eventual on-farm use (Stokes et al., 2012), as washing feet has shown to increase foot temperature variability (Main et al., 2012) and heat loss to the environment (Stewart et al., 2005).

After imaging, both of the rear feet were lifted in turn. The Dutch 5-step foot-trimming technique was employed. In so doing, the presence and location of DD and/or claw horn lesions were identified. Information on the diagnosis of the foot condition present and its severity were recorded for each foot. Pictorial paper ‘foot maps’ were also used to mark the precise location of lesions in lame cows. Throughout the entire imaging process, any fresh faeces were quickly cleared away from the imaging area and feet to remove sources of heat artefacts. The feet of control cows were imaged, inspected and lightly trimmed in the same way as lame cows to confirm an absence of pathology. Farm records on disease treatment were also checked to confirm that these cows had no other identified disease.

As the IRT images were taken before the veterinary inspection, images were collected from all 51 cows inspected. Of these, 17 were diagnosed with infectious disease (digital dermatitis or inter-digital dermatitis) and 21 classed as healthy and without disease. Six cows had a claw horn lesion, four had stones lodged in their hooves and the remainder had advanced slurry heel. Because of this prevalence pattern, only images from the healthy cows and those with DD were analysed.

Environmental conditions can influence the temperature detected by the imager, therefore monitoring temperature and humidity is extremely important whilst conducting thermal imaging (Main et al., 2012). A Kestrel 4000 Weather Meter was used throughout this experiment to monitor atmospheric temperature and relative humidity and ensure that the ‘object parameter’ settings on the thermal camera were adjusted accordingly. Imaging was conducted in a covered barn away from direct sunlight and air movement, ensuring that as much control as possible was held over radiant heat and windspeed. By taking images of lame and healthy cows on the same day, we controlled for effects of temperature and humidity. However, ambient temperature was also recorded at each session so that it could be taken into account in the analysis. Ambient temperature ranged from 3-16°C.

Thermal imaging camera

A FLIR SC620 high performance infra-red thermal imaging camera was used to take the images throughout the study. The temperature range of the camera was -40ºC to 500ºC with a thermal sensitivity of ± 0.04°C and an accuracy of ± 1% of reading in this restricted range. The wide angle lens was 45º x 34º (f=19mm), had a spatial resolution of 0.65mrad. IR resolution was 640x480 pixels. Emissivity was set to 0.98, distance from object 1 m, FOV 46 and reflective temperature at 25ºC. A Level 1 certified thermographer (MF) was responsible for capturing all images.

Image analysis and data extraction

Typically, only one image of each anatomical area was taken. If more than one was taken, the image with the best view of the area concerned and/or the best clarity of focus was chosen. These images were then analysed. Therma-CAM Researcher Professional 2.10 software was used for image analysis and extraction. After each image was loaded into the software, a polygon tool was used to trace around the desired anatomical area. To ensure consistency in the analysis across all of the feet assessed in the study, a defined anatomical area of the foot was always selected according to rules shown in Table 1. The software was then used to extract the temperature values from the area outlined by the polygon tool. The extracted temperature data from the selected region was converted to comma separated values using Microsoft Excel 2010. The data from each thermogram of each foot then saved in a single spreadsheet.

Temperature data analysis

The spreadsheet for each area was imported into Minitab v15, where the data was stacked. For each foot, the maximum, mean, 90th percentile, 95th percentile, coefficient of variation and standard deviation of the temperature values were calculated. The distribution of these measures across the whole dataset was plotted. The distributions were normal, so parametric statistical methods were used.

Statistical methods

The veterinary diagnosis made for each cow on the day of data collection was used as to categorise the cow and each of the hind feet of the cow as 'healthy' or 'lame'. The aim of the statistical analysis was to find the statistical descriptors and foot anatomical area that was associated with the lameness status of the foot, as a means of identifying the cow as being lame and which foot was lame. The data for each anatomical area between lame and healthy feet were initially inspected using histograms to assess the distribution of the data and presence of outlying values. To determine whether the summary statistics that we considered were highly correlated (and therefore giving us the same information) the level of association between these data summary statistics was explored using scatter plots and Pearson's Product Moment correlations.

General linear models were then used to assess the association between lameness and the statistical descriptors. Models were fitted to all cows (lame and sound) with a view to identification of lameness of all animals in the sample group. Then, because in some applications, once the cow is identified as lame it may be necessary for an automated system to detect the lame foot on a lame cow, models were fitted to only lame cows to assess ability of IRT to detect the lame from the sound foot. As ambient temperature has been shown to be correlated with foot temperature (Stokes et al; 2012; Alsaaod and Büscher, 2012; Wood et al., 2015), ambient temperature at the time the image was taken was included as a fixed effect. Cow identity was fitted as a random effect as measurements from two feet were used for each cow. F statistics (F) and the degrees of freedom (d.f.) of the comparison of the treatment (d.f.=1) and the residuals is shown. An ANOVA was used to determine whether the healthy foot of lame cows had a higher temperature than healthy feet on healthy cows. The treatments stratum included cow lameness status and foot lameness status, with ambient temperature as a covariate.

Sensitivity (proportion of positives correctly identified), specificity (proportion of negatives correctly identified) and the trade-off between the two, are important factors to consider when deciding how useful thermal imaging is as a diagnostic method and which area and measures give the best outcome. The decision theoretic value of the different descriptors was assessed by receiver operating characteristic (ROC) curve analysis, treating the summary statistics as markers to be dichotomised with a single cut-off to give a diagnostic decision. The ROC graph plots the proportion of true positives against the proportion of false positive for a range of possible settings of the decision criteria. Individual producers may vary in their risk averseness. The more risk averse producer may be willing to accept a system that gives a few false positives, and take the time to inspect the feet of these cows, as long as all true positives are detected. A risk prone producer may prefer a system in which fewer are inspected, but the majority are true positives. The ROC curve represents all combinations of these strategies. However, optimal values were also calculated for sensitivity, specificity and cut-off points using the using OptimalCutpoints package in R.

In this case the decision criteria for the ROC analysis were levels of the different statistical descriptors (Swets, 1988). The ROC analysis was based on decision making at a cow level, treating the cow as a unit that could be lame or sound. This required each cow's two hind feet measurements to be combined to produce a cow level result. Two approaches were used: the maximum value from both feet and the difference between the values from each foot, for each foot-level statistic. Ambient temperature was taken into account by firstly modelling the measured value for each foot with ambient temperature as sole predictor and calculating the residual effects to allow for adjustment.
The R statistical software (R Core Team 2017) was used for data manipulation, exploration and model fitting. Statistical significance was set at $P<0.05$.

Results

Data

Data from the 17 cows diagnosed with infectious disease and the 21 without disease were examined. Firstly, the correlation between the different statistical descriptors was assessed to determine whether they conveyed the same information. There was a high level of correlation between the statistical measures of central tendency (mean, maximum, 90^{th} and 95^{th} percentile) for both the coronary band and the heels (Figures 1a and b). Likewise, the measures of variance (standard deviation (SD) and coefficient of variation (CoV)) were also highly correlated, but there was a low correlation between measures of central tendency (e.g. mean, maximum and percentiles) and variance statistics (SD and CoV). Exploratory plots and information from previous studies suggested that the maximum (Max), 95^{th} percentile (95PCT) and standard deviation (SD) were the most useful to analyse, so only the results from these statistical descriptors will be shown in the rest of the results.

Lame vs healthy feet across all cows

To assess the utility of the statistical descriptors in detecting lameness, analyses were done on two sets of data. Firstly, regression models were used to determine whether there were differences between the lame and healthy feet of all cows reflected in the statistical descriptors, irrespective of whether the cow was classed as healthy or lame. A number of previous studies have taken this approach (e.g. Alsaaod and Büscher, 2012; Main et al., 2012). A number of descriptors showed statistically significant differences between lame and healthy feet at the two anatomical locations (Table 2). At the heels, lame feet had significantly higher 95PCT values ($F=4.81$, d.f.= 1, 39; $P=0.034$) and higher standard deviation values ($F=4.26$, d.f.= 1, 47, $P=0.044$) than healthy feet. At the coronary band, lame feet had higher standard deviations values ($F=6.212$, d.f.= 1,50; $P=0.016$). There was a tendency for lame feet to have higher maximum ($F=3.83$, d.f.1,44; $P=0.057$) and 95PCT ($F=3.41$, d.f.=1,43; $P=0.072$) values than healthy feet at the coronary band (Table 2).

Detecting the lame foot of a cow identified as lame (within cow analysis)

The analysis of the lame cows only also showed that a number of the measures differed between lame and healthy feet (Table 3). The 95PCT values were higher in the heel of the lame foot compared to the heel of the healthy foot (F=5.02, d.f.=1,16, P=0.04) of these lame cows. At the coronary band, the maximum temperature was higher in the lame foot (F=4.58, d.f.=1,16, P=0.048) and there was a tendency for the standard deviation to be higher in the lame foot (F=3.69, d.f.=1,16, P=0.073) than the healthy foot.

Differences between lame and healthy cows

The ANOVA analyses on each measure showed no significant effect of the lameness status (lame vs. healthy) of the cow (All P<0.05). However, the data suggest even the healthy feet of the lame cows are showing higher temperatures and temperature variation than the feet of healthy cows (Figure 2).

ROC analysis

The ROC analysis and examination of the area under the curve (AUC) values for the different measures suggested that using the maximum temperature found across both hind feet at the heels gave an AUC of 0.72 (Table 3). Using the 95^{th} percentile also gave a reasonably high AUC measure of 0.68, also at the heels. The maximum values gave better AUC values than the measures of the differences between the two feet.

Discussion

There were significant differences between lame and healthy feet in a number of the statistical descriptors at the two anatomical locations, confirming the utility of IRT in detecting lameness in dairy cattle. The maximum temperature is the measure that other studies have used to distinguish lame from healthy feet at both the coronary band (e.g. Nikkhah et al., 2005; Alsaaod and Büscher 2012) and plantar aspect of the pastern (e.g. Main et al., 2012; Stokes et al., 2012; Wood et al; 2014). The present study shows that other descriptors, such as the 95PCT and standard deviation can also be used to distinguish lame from healthy feet. In terms of the most appropriate area to use to detect lameness, differences were evident at both the coronary band and the rear section of the pastern. The ROC analysis suggested that images taken of the heels gave the best result as the maximum temperature at the heels gave the highest AUC value of 0.72. This value is in the range shown by other studies (Alsaaod and Büscher, 2012; Alsaaod et al., 2014).

The results of this study have also shown that statistical descriptors other than the maximum temperature can be used to detect lameness. The 95th percentile was a measure that was particularly useful, particularly in the plantar aspect of the pastern. Additionally, the standard deviation of the temperatures was also significantly higher in lame feet compared to healthy feet. Any inflammation present within the image would increase the range of temperatures present. These statistical descriptors may be useful in areas where there are contamination 'hotspots' from urine or faeces. The plantar aspect of the pastern is quite likely to suffer from this. It may be useful to use a number of measures in combination to increase the accuracy of diagnosis, and reduce the false positive rate. A larger sample size of animals than was available for this study would allow this analysis to be done.

Capturing data from the correct anatomical location in each IRT image and calculating the summary statistics required manual extract by a trained operator using specialised software, and was relatively time-consuming. The time-course and technical requirements of this process meant that it is not currently practical to allow instantaneous detection of lame cows on dairy farms. Full automation of such a system would firstly require a feature recognition system that could recognise the appropriate area (e.g. coronary band), followed by a system to extract and analyse the data to determine whether disease is present. With a more widespread application of this type of technology and the rise of precision livestock farming, this is not inconceivable in the future. Robotic milking systems may provide an ideal platform for this technology.

The graphical results suggest that the temperature of both feet of a cow diagnosed as being lame are elevated, despite veterinary examination confirming that only one of the feet was affected with DD. While there may be variation between cows in their core body temperature while healthy, this suggests that there may be systemic inflammatory processes involved that lead to an overall elevated body temperature or that in an attempt to take pressure off the lame foot when standing or walking, the additional pressure placed on the healthy foot resulted in increased temperatures in the healthy foot. The finding that the highest measure from either foot was a better diagnostic tool than taking the difference between the feet also confirmed this. Wood et al. (2014) also found less consistent diagnosis of lameness when using the temperature difference between the lame foot and the contralateral healthy foot, compared to using the actual foot temperature. This suggests that using the contralateral foot as the 'control' may not be appropriate, and this should be taken into account when considering the use of IRT in detecting lameness in a commercial setting.

Alsaaod et al. (2014) suggested that IRT can only be used successfully as a diagnostic tool on clean feet, due to dirt having a considerable effect on emissivity and heat loss (Stewart et al., 2005). This is in contrast to the conclusions of Stokes et al. (2012) who found that the diagnostic accuracy was higher in uncleaned feet. Cleaning the feet, for instance, by hosing with water or brushing, would remove the mud or bedding, but wetting the hair or creating friction during brushing disturbs the temperature profile of the affected area, making diagnosis more difficult. The feet of the cows in this study were not cleaned prior to imaging. However, as these cows were housed indoors in cubicle sheds with frequently scraped concrete floors they may have been cleaner than animals which have been grazing or been housed in deep-bedded systems,. The results of this study suggest that in this type of housing system, which is commonly used in the UK and more widely, thermal imaging on unwashed feet can detect DD with some success.

When a continuous or ordinal marker is used to create a binary diagnostic test (lame or not lame in this case) there is always a trade-off between specificity and sensitivity unless the distribution of the marker in the population of healthy individuals has absolutely no overlap with the distribution for unhealthy animals. Depending on their lameness management strategy, farmers may favour different strategies. For instance, a farmer may take a conservative approach in which a cut-off point is chosen with a high sensitivity but lower specificity. This approach would identify all lame cows, but as the IRT markers of DD are not definitive enough to be used as a binary diagnostic test, would also classify some non-lame cows as lame, with potential labour costs of inspecting non-lame cows.

An alternative low sensitivity and high specificity strategy would mean that only lame cows were examined, but some lame cows were not detected and examined.

Conclusions

The AUC analysis suggested that the maximum temperature measured at the heels had the highest accuracy in detecting lameness. This confirms results of previous studies. However, the use of the 95th percentile, and the standard deviation also allowed lame feet to be distinguished from non-lame feet and gave good AUC values. These alternative statistical descriptors may be particularly useful in situations where there is high probability of contamination of the target area. Despite the heel area being at risk of contamination through dirt and faeces, the ROC analysis suggested that measurements taken in this area give the best chance of accurately predicting lameness in housed dairy cattle.

Conflict of interest statement

None of the authors has any financial or personal relationship with any commercial company that could influence the results of this study or result in any bias.

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Table 1

The rules applied to each IRT image to select the area for data capture for the coronary band and heel.

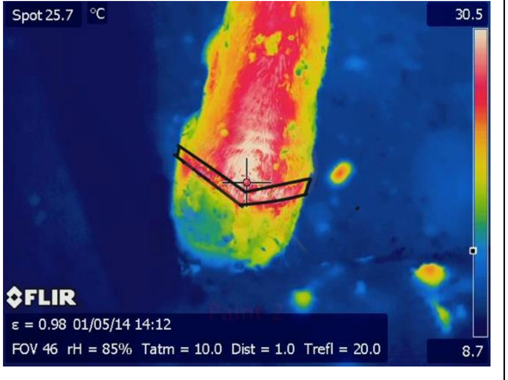
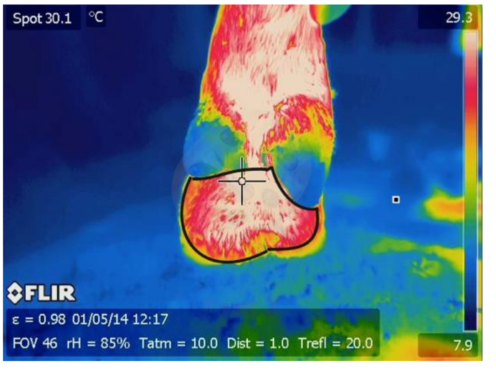
<table>
<tr><th>Area</th><th>Rule</th><th>Example</th></tr>
<tr><td>Coronary band</td><td>Area at the top of the foot above the hoof wall where the hair is sparse and a band of skin is visible. A ‘V’ shape was drawn using data capture software.</td><td>
</td></tr>
<tr><td>Plantar aspect of the pastern</td><td>Plantar aspect of the pastern: the area from underneath the digits, to the base of the foot.</td><td>
</td></tr>
</table>

Table 2

Table showing raw data for the different statistical measures for the healthy feet of healthy (control) cows and the healthy and lame feet of the lame cows. All measures are in C°.

Statistical measure	Cow class	Leg class	Anatomical location	
			Coronary Band	Heel
Mean	Healthy	Healthy	26.2 (2.69)	24.7 (2.71)
	Lame	Lame	26.9 (2.37)	26.5 (2.52)
		Healthy	26.7 (1.87)	26 (2.26)
95th percentile	Healthy	Healthy	30.2 (2.84)	28 (2.71)
	Lame	Lame	31.6 (1.7)	30 (2.29)
		Healthy	30.9 (1.73)	29.3 (2.29)
Maximum	Healthy	Healthy	31.6 (2.81)	30.1 (2.54)
	Lame	Lame	33.4 (1.37)	31.9 (2.36)
		Healthy	32.7 (1.41)	31.5 (2.46)
Standard deviation	Healthy	Healthy	2.34 (0.529)	2.24 (0.5)
	Lame	Lame	2.8 (0.642)	2.59 (0.785)
		Healthy	2.58 (0.519)	2.34 (0.509)

Table 3

Table showing area under the curve AUC 95th % confidence interval. and sensitivity (SE), specificity (SP) and cut-off point at the optimal point AUC and for the two anatomical locations (coronary band and heel) and the different statistical measures calculated for the maximum value found on both feet (Maximum) and for the absolute difference between them (difference). All measures are in C°. Values have been adjusted for ambient temperature.

Location	**Foot Level Measure**	**Cow Level Comparator**	**AUC (CI)**	**SE**	**SP**	**Cut-off point**
Heel	Max	maximum	0.72 (0.54 - 0.9)	0.74	0.68	0.29
Heel	95PCT	maximum	0.68 (0.49 - 0.87)	0.65	0.71	0.35
Heel	Mean	maximum	0.64 (0.46 - 0.83)	0.59	0.58	0.32
Heel	SD	maximum	0.55 (0.35 - 0.74)	0.53	0.58	0.04
Heel	Max	difference	0.56 (0.37 - 0.76)	0.59	0.58	-0.37
Heel	95PCT	difference	0.63 (0.44 - 0.83)	0.35	0.53	-0.20
Heel	Mean	difference	0.62 (0.43 - 0.81)	0.41	0.42	-0.21
Heel	SD	difference	0.55 (0.35 - 0.75)	0.53	0.58	-0.06
Coronary band	Max	maximum	0.65 (0.46 - 0.83)	0.59	0.66	0.55
Coronary band	95PCT	maximum	0.63 (0.45 - 0.82)	0.59	0.63	0.47
Coronary band	Mean	maximum	0.49 (0.29 - 0.68)	0.56	0.42	-0.45
Coronary band	SD	maximum	0.67 (0.48 - 0.87)	0.65	0.79	0.00
Coronary band	Max	difference	0.53 (0.33 - 0.73)	0.47	0.47	-0.31
Coronary band	95PCT	difference	0.52 (0.32 - 0.72)	0.53	0.42	-0.46
Coronary band	Mean	difference	0.61 (0.42 - 0.8)	0.50	0.37	-0.60
Coronary band	SD	difference	0.53 (0.33 - 0.72)	0.62	0.58	-0.07

Figure legends

Figure 1. Chart showing correlations between the statistical descriptors for the coronary band (Figure 1a) and for the heels (Figure 1b). Cells on the diagonal show the parameter. Above the diagonal the correlation value is shown, with the size of the font indicating the size of the correlation. A pictorial of the correlation is shown below the diagonal.

Figure 2. Graphs showing each of the temperature statistical descriptors (95th PCT, maximum, mean and standard deviation) for the coronary band (CB) and heel (H). Each chart, the data for both hind feet of the healthy cows (control) is shown on the left. In the right portion of each graph, the data from healthy foot and the lame foot of the lame cows is shown, with the healthy foot on the left and the lame foot on the right. The vertical length of the line represents the 95th confidence interval and the point is the mean. The y-axis shows temperature (C) for 95th PCT, Max and Mean, and shows standard deviation values for SD.