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Original article

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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22 **Abstract**

23 Lameness in dairy cattle is a persistent problem, indicating pain caused by underlying disease
24 states and is associated with reduced milk yields. Digital dermatitis is a common cause of lameness.
25 Thermal imaging is a technique that may facilitate early detection of this disease and has the potential
26 for use in automated detection systems. Previous studies with thermal imaging have imaged either the
27 heels or the coronary band of the foot and typically only used the maximum temperature (Max) value
28 as the outcome measure. This study investigated the utility of other statistical descriptors: 90th
29 percentile (90PCT), 95th percentile (95PCT), standard deviation (SD) and coefficient of variation
30 (CoV) and compared the utility of imaging the heel or coronary band. Images were collected from
31 lame and healthy cows using a high-resolution thermal camera. Analyses were done at the cow and
32 foot level. There were significant differences between lame and healthy feet detectable at the heels
33 (95th percentile: $P < 0.05$; SD: $P < 0.05$) and coronary band (SD: $P < 0.05$). Within lame cows, 95PCT
34 values were higher at the heel ($P < 0.05$) and Max values were higher at the coronary band ($P < 0.05$) in
35 the lame foot compared to the healthy foot. ROC analysis showed an AUC value of 0.72 for Max
36 temperature and 0.68 for 95PCT at the heels. It was concluded that maximum temperature is the most
37 accurate measure, but other statistical descriptors of temperature can be used to detect lameness.
38 These may be useful in certain contexts, such as where there is contamination. Differentiation of lame
39 from healthy feet was most apparent when imaging the heels.

40

41

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

43

44 **Introduction**

45 Lameness is one of the most common production diseases affecting modern dairy cows. It is
46 recognised as causing pain (Whay et al., 1998) and is associated with reduction in milk yield (Green
47 et al., 2002; Archer et al., 2010) and fertility (Hultgren et al., 2004). The incidence of lameness has
48 been reported as varying between 21 and 69% in North America (Cook, 2003; Solano et al., 2015)
49 and from 21 % to 37% in the United Kingdom, varying with the grazing and housing system used
50 (Rutherford et al., 2009; Barker et al., 2010). In particular, digital dermatitis (DD) is currently one of
51 the most prevalent infectious diseases associated with lameness, affecting around 70% of all UK dairy
52 herds (Archer et al., 2010). Within-herd prevalence of digital dermatitis has been estimated as
53 between 0 and 74% (Somers et al., 2005; Holzhauser et al., 2006; Solano et al., 2015; Jacobs et al.,
54 2017).

55

56 Early detection of infectious conditions such as digital dermatitis facilitates prompt treatment,
57 and is considered the best method of reducing the overall severity of the disease (Stokes et al., 2012;
58 Alsaad et al., 2014). Such timely detection and treatment of conditions leading to lameness will not
59 only prevent progression of the condition (Leach et al 2012), but will reduce the level of the infective
60 reservoir within the herd (Stokes et al., 2012). However, this requires that producers have a reliable
61 method of detecting DD available to them, as well as the time and resources to provide appropriate
62 treatment and care. Changes in locomotion or gait characteristics are often the first detectable signs of
63 foot disease. Visual gait scoring methods have been developed to assess lameness (e.g. Manson and
64 Leaver, 1988; Sprecher et al., 1997). However, despite the presence of these systems and other
65 initiatives, prevalence remains high. For instance in the UK, a prevalence of 36.8% was reported in
66 2010 by Barker et al., which is comparable to the prevalence of 31.6% found in a recent study
67 (Griffiths et al., 2018). Automated systems of lameness detection may be useful, so that the farmer
68 does not need to set aside time to observe cows walking. There are automated systems assessing
69 pressure and force of cows' feet when walking or standing (e.g. Rajkondawar et al., 2006; Pastell et
70 al., 2010; Maertens et al., 2011) and more recently, systems have been developed to detect the change

71 in feeding behaviour and activity associated with lameness (e.g. Mazrier et al., 2006; Blackie et al.,
72 2011; Beer et al., 2016). However, the use of more than one type of sensor has been suggested as a
73 way of increasing the accuracy of detection of issues (Borchers et al., 2017). As well as some measure
74 of change in activity, another independent variable such as a measure of infection, would improve
75 detection rates.

76

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

93

94 Infrared thermography has been used previously to detect foot conditions associated with
95 lameness in horses (Turner, 1991; Eddy et al., 2001) and changes in udder temperature associated
96 with mastitis in dairy cows (Berry et al., 2003). Previous studies have also shown that thermal
97 imaging or thermography can be used in cattle to differentiate between feet affected by lameness-
98 causing lesions and healthy feet (Alsaad and Büscher, 2012; Stokes et al., 2012; Alsaad et al.,

99 2014). Non-contact infra-red thermometry has shown similar results (Main et al., 2012; Wood et al.,
100 2014). These studies have involved imaging two major parts of the feet, the coronary band (e.g.
101 Nikkhah et al., 2005; Alsaad and Büscher, 2012; Alsaad et al., 2014) and the rear aspect of the hind
102 feet above the heel bulbs (Main et al., 2012; Stokes et al., 2012). The majority of these studies used
103 the maximum temperature detected in the target area as an indicator of the presence of lameness in the
104 foot. However, it is possible that the presence of a lesion or an inflammatory condition might be more
105 accurately detected by using other statistical descriptors of the data obtained from a spatial profile of
106 surface temperatures in the target area.

107

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

114

115 **Materials and Methods**

116 *Animals, husbandry and management*

117 This study was conducted using an experimental herd of 200 Holstein dairy cattle, based at
118 Crichton Royal Farm, Dumfries, Scotland. The study methods were approved by Scotland's rural
119 College's Animal Experiments Committee (Submission number: ED AC 45-2013) on 26th November,
120 2013. The herd was managed in two separate feeding and management systems as part of an
121 experiment investigating the effects of genetic line (high genetic merit for milk yield vs. a control
122 line) and management (indoor housing/bought in feeds vs. outdoor housing in summer/feedstuffs
123 grown on the farm) on milk yield and health. Cows were removed from the herd following the fourth
124 lactation and herd turnover was around 25% annually. Historically, digital dermatitis has been the
125 most prevalent infectious condition causing lameness in the herd throughout the year, with a

126 prevalence of 2-3%, and the prevalence of solar ulcers is 1% or less. The overall prevalence of
127 lameness is 8% (Chagunda, 2012).

128

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

142

143 *Lameness scoring and foot examination*

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

149

150 *Foot examination and image collection*

151 Foot examination took place in a claw trimming crush and was carried out by an experienced
152 veterinary surgeon (CM). All cows identified as lame were separated from their management groups
153 and held as a group in a holding pen beside the crush. Control cows, with a locomotion score of 1,

154 were also identified, observed again to confirm this score, and included in this group in the holding
155 pen. One by one, each cow was inspected in the crush. Before any handling of the feet took place,
156 images were taken of the front of the coronary band and the plantar aspect of the pastern joint (image
157 taken from ground level of the area between the heel bulbs and the dew claws) of both rear feet. The
158 feet were not cleaned with water or by any other method. Using only dirty feet not only makes results
159 more applicable for eventual on-farm use (Stokes et al., 2012), as washing feet has shown to increase
160 foot temperature variability (Main et al., 2012) and heat loss to the environment (Stewart et al., 2005).

161

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

171

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

177

178 Environmental conditions can influence the temperature detected by the imager, therefore
179 monitoring temperature and humidity is extremely important whilst conducting thermal imaging
180 (Main et al., 2012). A Kestrel 4000 Weather Meter was used throughout this experiment to monitor
181 atmospheric temperature and relative humidity and ensure that the ‘object parameter’ settings on the

182 thermal camera were adjusted accordingly. Imaging was conducted in a covered barn away from
183 direct sunlight and air movement, ensuring that as much control as possible was held over radiant heat
184 and windspeed. By taking images of lame and healthy cows on the same day, we controlled for effects
185 of temperature and humidity. However, ambient temperature was also recorded at each session so that
186 it could be taken into account in the analysis. Ambient temperature ranged from 3-16°C.

187

188 *Thermal imaging camera*

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

195

196 *Image analysis and data extraction*

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

207

208 *Temperature data analysis*

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

214

215 *Statistical methods*

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

225

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

236 foot of lame cows had a higher temperature than healthy feet on healthy cows. The treatments stratum
237 included cow lameness status and foot lameness status, with ambient temperature as a covariate.

238

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

252

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

262

263 **Results**

264 *Data*

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

275

276 *Lame vs healthy feet across all cows*

277 To assess the utility of the statistical descriptors in detecting lameness, analyses were done on
278 two sets of data. Firstly, regression models were used to determine whether there were differences
279 between the lame and healthy feet of all cows reflected in the statistical descriptors, irrespective of
280 whether the cow was classed as healthy or lame. A number of previous studies have taken this
281 approach (e.g. Alsaad and Büscher, 2012; Main et al., 2012). A number of descriptors showed
282 statistically significant differences between lame and healthy feet at the two anatomical locations
283 (Table 2). At the heels, lame feet had significantly higher 95PCT values ($F=4.81$, d.f.= 1, 39;
284 $P=0.034$) and higher standard deviation values ($F=4.26$, d.f.= 1, 47, $P=0.044$) than healthy feet. At the
285 coronary band, lame feet had higher standard deviations values ($F=6.212$, d.f.= 1,50; $P=0.016$). There
286 was a tendency for lame feet to have higher maximum ($F=3.83$, d.f.1,44; $P=0.057$) and 95PCT
287 ($F=3.41$, d.f.=1,43; $P=0.072$) values than healthy feet at the coronary band (Table 2).

288

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

290 The analysis of the lame cows only also showed that a number of the measures differed
291 between lame and healthy feet (Table 3). The 95PCT values were higher in the heel of the lame foot

292 compared to the heel of the healthy foot ($F=5.02$, $d.f.=1,16$, $P=0.04$) of these lame cows. At the
293 coronary band, the maximum temperature was higher in the lame foot ($F=4.58$, $d.f.=1,16$, $P=0.048$)
294 and there was a tendency for the standard deviation to be higher in the lame foot ($F=3.69$, $d.f.=1,16$,
295 $P=0.073$) than the healthy foot.

296

297 *Differences between lame and healthy cows*

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

302

303 *ROC analysis*

304 The ROC analysis and examination of the area under the curve (AUC) values for the different
305 measures suggested that using the maximum temperature found across both hind feet at the heels gave
306 an AUC of 0.72 (Table 3). Using the 95th percentile also gave a reasonably high AUC measure of
307 0.68, also at the heels. The maximum values gave better AUC values than the measures of the
308 differences between the two feet.

309

310 **Discussion**

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

320 the heels gave the highest AUC value of 0.72. This value is in the range shown by other studies
321 (Alsaad and Büscher, 2012; Alsaad et al., 2014).

322

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

332

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

342

343 The graphical results suggest that the temperature of both feet of a cow diagnosed as being
344 lame are elevated, despite veterinary examination confirming that only one of the feet was affected
345 with DD. While there may be variation between cows in their core body temperature while healthy,
346 this suggests that there may be systemic inflammatory processes involved that lead to an overall
347 elevated body temperature or that in an attempt to take pressure off the lame foot when standing or

348 walking, the additional pressure placed on the healthy foot resulted in increased temperatures in the
349 healthy foot. The finding that the highest measure from either foot was a better diagnostic tool than
350 taking the difference between the feet also confirmed this. Wood et al. (2014) also found less
351 consistent diagnosis of lameness when using the temperature difference between the lame foot and the
352 contralateral healthy foot, compared to using the actual foot temperature. This suggests that using the
353 contralateral foot as the 'control' may not be appropriate, and this should be taken into account when
354 considering the use of IRT in detecting lameness in a commercial setting.

355

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

367

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

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

378

379 **Conclusions**

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

388

389 **Conflict of interest statement**

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

392

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397

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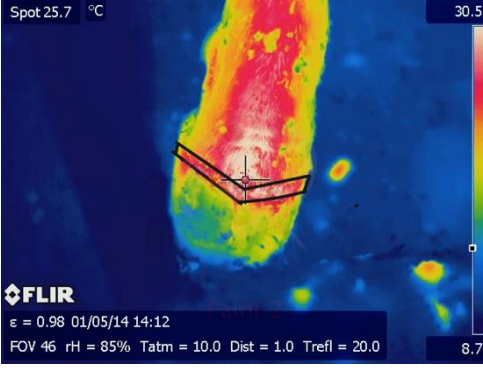
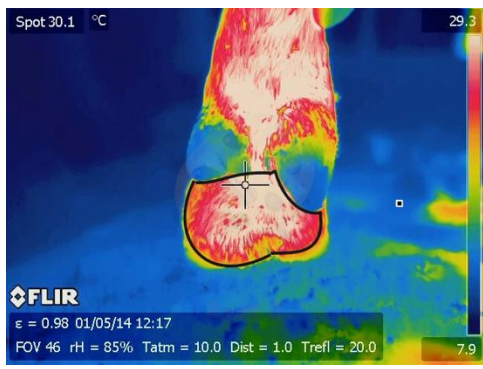
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492 **Table 1**

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

Area	Rule	Example
Coronary band	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.	
Plantar aspect of the pastern	Plantar aspect of the pastern: the area from underneath the digits, to the base of the foot.	

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497 **Table 2**

498 Table showing raw data for the different statistical measures for the healthy feet of healthy (control)
 499 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)
95 th percentile		Healthy	26.7 (1.87)	26 (2.26)
	Healthy	Healthy	30.2 (2.84)	28 (2.71)
	Lame	Lame	31.6 (1.7)	30 (2.29)
Maximum		Healthy	30.9 (1.73)	29.3 (2.29)
	Healthy	Healthy	31.6 (2.81)	30.1 (2.54)
	Lame	Lame	33.4 (1.37)	31.9 (2.36)
Standard deviation		Healthy	32.7 (1.41)	31.5 (2.46)
	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)

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502 **Table 3**

503 Table showing area under the curve AUC 95th % confidence interval. and sensitivity (SE), specificity
 504 (SP) and cut-off point at the optimal point AUC and for the two anatomical locations (coronary band
 505 and heel) and the different statistical measures calculated for the maximum value found on both feet
 506 (Maximum) and for the absolute difference between them (difference). All measures are in C°. Values
 507 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

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510 Figure legends

511 Figure 1. Chart showing correlations between the statistical descriptors for the coronary band (Figure
512 1a) and for the heels (Figure 1b). Cells on the diagonal show the parameter. Above the diagonal the
513 correlation value is shown, with the size of the font indicating the size of the correlation. A pictorial
514 of the correlation is shown below the diagonal.

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