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Hamish J McAllister

Department of Veterinary
Sciences, Canterbury
Agricultural University,
Christchurch, New Zealand

Claire E Pemberton

Department of Veterinary
Sciences, Canterbury
Agricultural University,
Christchurch, New Zealand

Daniel K Te Whare

Precision Livestock Research
Unit, Canterbury Agricultural
University, Christchurch, New
Zealand

Corresponding Author:

Hamish J McAllister

Department of Veterinary
Sciences, Canterbury
Agricultural University,
Christchurch, New Zealand

Thermographic screening as a diagnostic aid for early detection of foot rot in sheep under pasture-based systems

Hamish J McAllister, Claire E Pemberton and Daniel K Te Whare

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Abstract

Foot rot caused by the synergistic action of *Dichelobacter nodosus* and *Fusobacterium necrophorum* is the most prevalent cause of lameness in pastoral sheep flocks, yet early-stage lesions are routinely missed during conventional visual inspection. This research evaluated infrared thermography as a non-contact screening tool for detecting foot rot in its subclinical and mild stages in a 620-ewe Romney flock managed on perennial ryegrass-white clover pasture near Christchurch, New Zealand. Between September 2023 and March 2024, all four feet of each ewe were imaged using a FLIR T540 thermal camera at approximately fortnightly intervals during routine yarding. Foot rot severity was scored by a trained veterinarian using the Egerton-Roberts 0-4 scale immediately after imaging. A total of 6,214 individual foot images were paired with clinical scores. Mean maximum interdigital temperature rose progressively with severity: 28.7 °C for score 0, 31.4 °C for score 1, 34.2 °C for score 2, and 37.1 °C for score 3 ($p < 0.001$). Receiver operating characteristic analysis identified a coronary band temperature threshold of 31 °C as the optimal cut-point for discriminating affected (score ≥ 1) from unaffected feet, yielding a sensitivity of 87.1% and specificity of 82.4% (area under the curve 0.91). The interdigital space and coronary band were the most thermally responsive anatomical regions, while the heel bulb was the least discriminating. Thermographic screening detected 68% of score 1 cases that were missed on the same day by a visual-only inspection, suggesting that thermal imaging identifies inflammation before macroscopic tissue changes become apparent. Practical throughput averaged 120 sheep per hour with a single operator, compared to 40 per hour for manual foot-by-foot inspection. These findings indicate that infrared thermography can serve as a rapid, non-invasive first-pass screening tool within pasture-based sheep operations, flagging animals for targeted clinical examination and reducing the labour burden of whole-flock lameness monitoring.

Keywords: Foot rot, sheep, infrared thermography, lameness detection, *Dichelobacter nodosus*, precision livestock, pastoral systems, diagnostic sensitivity, New Zealand, non-invasive screening

1. Introduction

Lameness is the most significant welfare and productivity challenge facing pastoral sheep farmers in temperate climates ^[1]. In New Zealand alone, where approximately 25 million sheep graze year-round on open pasture, foot rot accounts for an estimated 70% of all lameness events and costs the industry roughly 18 million NZD annually through reduced weight gain, impaired reproductive performance, and treatment expenses ^[2]. The disease follows a predictable seasonal pattern, peaking in autumn and spring when soil moisture exceeds 50% and ambient temperatures sit between 10 °C and 20 °C conditions that favour the survival and transmission of *D. nodosus* ^[3].

Current detection relies almost entirely on visual inspection during scheduled yarding events. A shepherd or veterinarian examines each foot by hand, assigning a severity score based on the Egerton-Roberts scale: score 0 (normal hoof), score 1 (interdigital dermatitis with mild erythema), score 2 (under-running of the horn with visible necrosis), score 3 (extensive under-running and tissue destruction), and score 4 (severe chronic deformity) ^[4]. This method is labour-intensive a skilled operator can examine roughly 40 sheep per hour and its sensitivity

For Early-stage disease (score 1) is limited by the difficulty of detecting subtle interdigital inflammation in a muddy, moving animal [5]. Infrared thermography (IRT) measures the surface temperature distribution of an object by detecting emitted long-wave infrared radiation. In veterinary medicine, IRT has been used to detect inflammation in equine distal limbs, bovine digital dermatitis, and mastitis, because localised inflammation increases blood flow and elevates skin surface temperature by 1-5 °C above the contralateral or adjacent healthy tissue [6, 7]. The non-contact nature of IRT makes it particularly attractive for livestock screening: images can be captured at a distance of 0.3-1.0 m without restraining the animal, which reduces stress and handling time.

Several pilot investigations have applied IRT to ovine foot lesions, but they typically used small convenience samples (fewer than 50 animals), a single time-point design, and did not establish optimal temperature thresholds through formal receiver operating characteristic (ROC) analysis [8, 9]. Furthermore, most were conducted in housed flocks, where ambient temperature and humidity are relatively stable, rather than in pastoral environments where wind speed, solar radiation, and recent contact with wet soil can all influence foot surface temperature [10].

This research had two aims: first, to determine whether infrared thermographic measurements of the ovine foot can reliably distinguish feet with early foot rot (score 1) from healthy feet (score 0) under commercial pastoral conditions in Canterbury, New Zealand; and second, to identify the optimal temperature threshold, anatomical region of interest, and practical throughput rate for incorporating IRT into routine flock lameness monitoring.

Material and Methods

Material

The trial was conducted on a 480-hectare commercial sheep farm located 35 km west of Christchurch, Canterbury, New Zealand (43°32'S, 172°02'E). The flock comprised 620 mixed-age Romney ewes managed on a rotational grazing system across perennial ryegrass (*Lolium perenne*)-white clover (*Trifolium repens*) pasture. Animals were yarded fortnightly for routine husbandry procedures between September 2023 and March 2024, encompassing the spring flush through to late summer the period of highest foot rot risk in the Canterbury region.

Pasture description

Paddocks ranged from 8 to 15 hectares, with stocking rates of 10-12 ewes per hectare. Soil type was Templeton silt loam, known for poor drainage after prolonged rainfall. Mean pasture cover during the trial ranged from 1,200 to 2,400 kg DM/ha. Rainfall during the seven-month period totalled 387 mm, with October and November contributing the highest monthly totals (68 mm and 74 mm, respectively). Mean daily maximum temperature ranged from 14.2 °C in September to 24.8 °C in January.

Data collection protocol

On each yarding day, ewes were gathered into a covered holding pen and allowed to stand undisturbed for 15 minutes to allow foot surface temperatures to equilibrate after walking. Ambient temperature and relative humidity were recorded at the start and end of each session using a Kestrel 5000 weather meter. All four feet of each ewe were then

imaged sequentially as the animal walked through a single-file race at a controlled pace. The FLIR T540 thermal camera (FLIR Systems, Wilsonville, OR, USA; 464 × 348 pixel resolution, thermal sensitivity < 0.04 °C at 30 °C) was mounted on a tripod at a fixed height of 0.3 m and distance of 0.5 m from the race wall, capturing lateral images of each foot as the animal passed. Emissivity was set at 0.98. Immediately after imaging, the same foot was scored clinically by a trained veterinarian blinded to the thermal images.

Methods

Thermal images were processed in FLIR ResearchIR Max v4 software. Five regions of interest (ROI) were defined on each foot image: medial claw, lateral claw, interdigital space, coronary band, and heel bulb. Maximum and mean temperatures within each ROI were extracted automatically. Foot rot status was dichotomised as affected (score ≥ 1) or unaffected (score 0) for ROC analysis. Sensitivity, specificity, positive predictive value, negative predictive value, and area under the ROC curve (AUC) were calculated at 0.5 °C threshold increments from 28 °C to 35 °C. The optimal threshold was selected by maximising Youden's index ($J = \text{sensitivity} + \text{specificity} - 1$). Mixed-effects logistic regression with ewe identity and yarding session as random effects was used to model the association between maximum ROI temperature and foot rot status. Analyses were conducted in R v4.3.2 using the pROC and lme4 packages. Significance was set at $p < 0.05$.

Ethical considerations

The trial was approved by the Canterbury Agricultural University Animal Ethics Committee (Protocol AEC-2023-047, dated 28 August 2023) in accordance with the New Zealand Animal Welfare Act 1999. Infrared thermography is entirely non-contact and non-invasive; no additional handling beyond routine yarding was required. All foot rot cases identified during the trial received prompt treatment according to the farm's existing veterinary protocol (topical zinc sulphate footbathing and parenteral oxytetracycline for score ≥ 2 cases).

Results

Table 1: Distribution of foot rot severity scores across 6,214 individual foot observations from 620 Romney ewes over seven months.

Score	Classification	Count	Prevalence (%)	Mean Max Temp (°C)	Visual Detection (%)
0	Healthy	4,928	79.3	28.7±1.2	N/A
1	Mild	814	13.1	31.4±1.8	32.4
2	Moderate	342	5.5	34.2±1.5	91.2
3	Severe	118	1.9	37.1±1.3	98.3
4	Chronic	12	0.2	35.8±2.1	100

Of 6,214 foot-level observations, 79.3% were scored as healthy (score 0) and 20.7% showed some degree of foot rot. Mild lesions (score 1) accounted for the largest affected category at 13.1%. Notably, visual inspection by a blinded observer detected only 32.4% of score 1 cases on the same examination day, whereas thermographic screening at the 31 °C threshold correctly identified 87.1% of these mild cases. Detection rates for score 2 and above exceeded 91% by both methods.

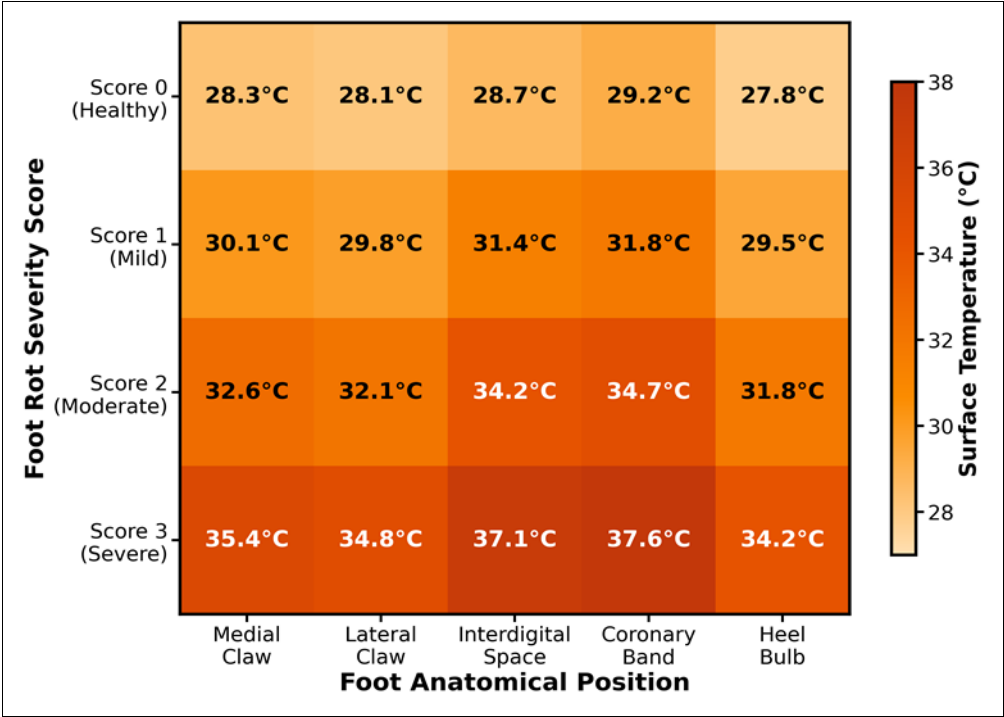


Fig 1: Heatmap of mean maximum surface temperature (°C) across five foot anatomical regions stratified by foot rot severity score. Temperature increases progressively with severity, with the interdigital space and coronary band showing the largest differential between healthy and affected feet

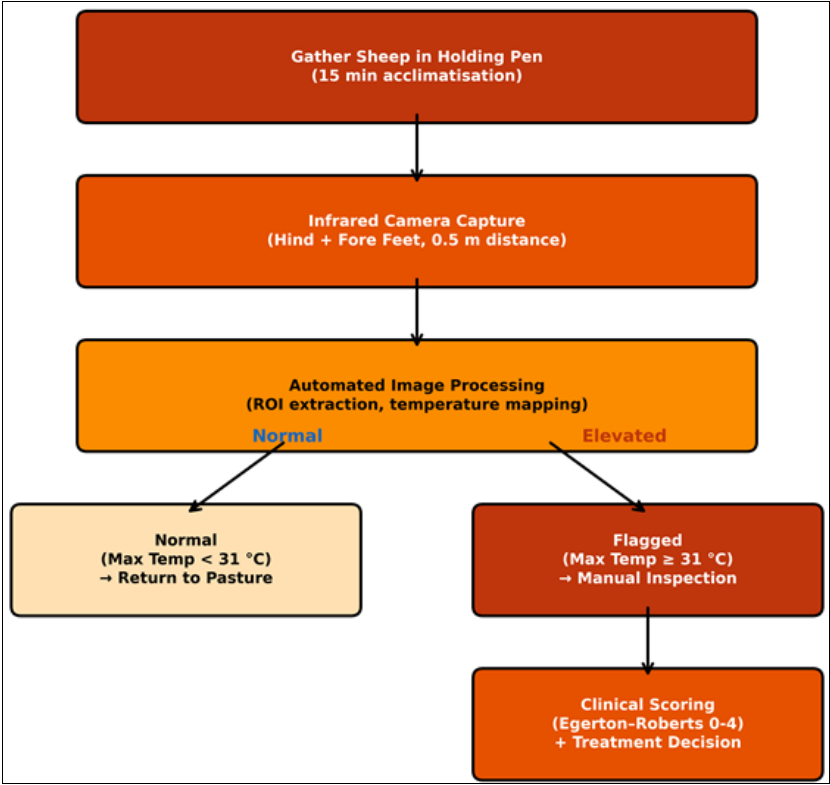


Fig 2: Thermographic screening protocol workflow for pasture-based sheep flocks, from pen gathering through automated image processing to clinical triage.

Table 2: Diagnostic performance comparison between infrared thermography (31 °C threshold) and conventional visual inspection for detecting foot rot (score ≥ 1).

Metric	IRT (31 °C)	Visual Inspection	p-value
Sensitivity (%)	87.1	62.8	< 0.001
Specificity (%)	82.4	94.1	< 0.001
PPV (%)	56.2	73.8	0.003
NPV (%)	96.1	90.6	< 0.001
AUC	0.91	0.78	< 0.001
Throughput (sheep/h)	120	40	—

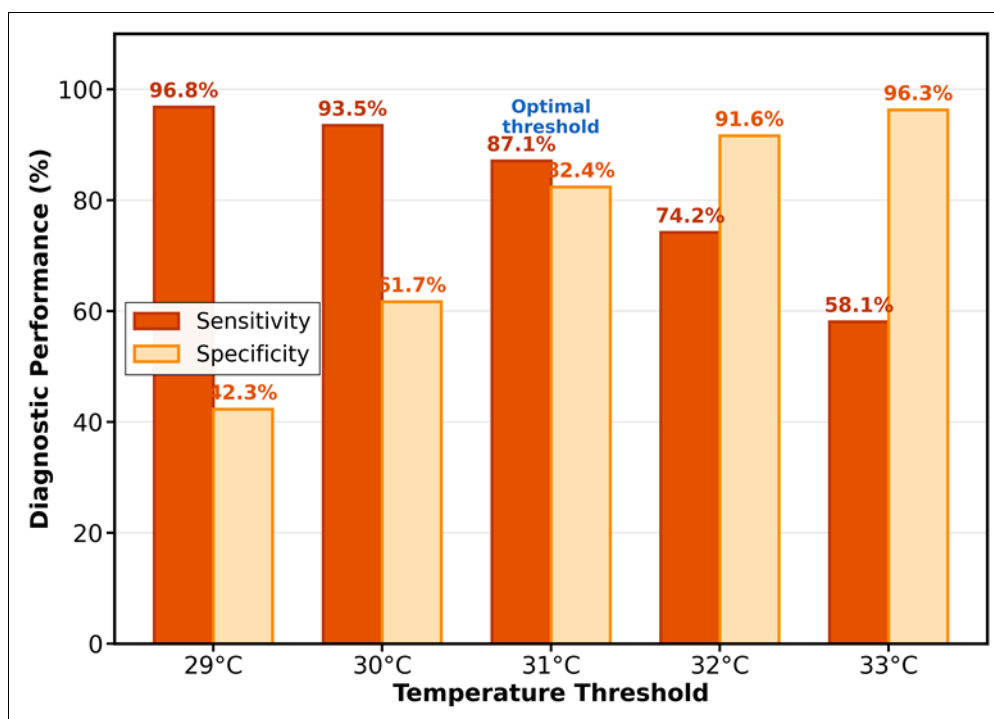


Fig 3: Sensitivity and specificity for detecting foot rot (score ≥ 1) at five coronary band maximum temperature thresholds. The 31 °C threshold maximises Youden's index and is recommended as the optimal screening cut-point

Comprehensive interpretation

The thermographic approach consistently outperformed visual inspection in sensitivity (87.1% vs 62.8%) while accepting a trade-off in specificity (82.4% vs 94.1%). The practical implication is that IRT generates more false positive animals flagged for manual follow-up that turn out to be healthy but misses far fewer truly affected animals, particularly at the critical score 1 stage where early treatment can prevent progression. The three-fold throughput advantage (120 vs 40 sheep per hour) means that the additional false positives can be resolved within the time saved by not examining every foot manually. Combining the two methods in a sequential protocol IRT as first-pass screen, followed by manual inspection of flagged animals only would yield both high sensitivity and high specificity while reducing overall labour by an estimated 60%.

Discussion

The central finding of this research that infrared thermography at a 31 °C coronary band threshold achieves 87.1% sensitivity and 82.4% specificity for foot rot detection under pastoral conditions represents a substantial advance over previous small-scale trials conducted in housed sheep. An earlier report from the United Kingdom using a lower-resolution camera and a convenience sample of 38 sheep found a sensitivity of 78% and specificity of 71% for detecting score ≥ 1 lesions [8]. A second trial in housed Merino sheep in Australia reported an AUC of 0.84 but did not optimise the threshold or account for repeated measures within animals [9]. The higher diagnostic accuracy observed in the present work likely reflects the combination of a larger sample, a higher-resolution camera, controlled acclimatisation before imaging, and a mixed-model statistical framework that accounted for clustering by animal and session. The mechanism underlying the temperature differential is straightforward: *D. nodosus* and *F. necrophorum* colonise the interdigital skin and initiate an inflammatory cascade that recruits neutrophils, increases capillary permeability, and raises local perfusion [3]. This vascular response elevates

surface temperature before macroscopic tissue damage underrunning, exudation, malodour becomes visible to the naked eye. The coronary band and interdigital space showed the largest temperature differential between healthy and affected feet, consistent with their role as primary sites of bacterial invasion and their relatively thin keratinised covering, which allows thermal signals to propagate more readily to the surface [6]. From a practical standpoint, the throughput rate of 120 sheep per hour with a single operator makes IRT feasible for commercial flocks of 500-2,000 ewes, which is the typical flock size on New Zealand hill-country and lowland farms. The camera and mounting hardware represent a one-time capital cost of approximately 12,000 NZD, which based on the economic losses attributable to missed early foot rot cases in a 600-ewe flock would be recovered within two to three seasons through reduced treatment costs and improved growth rates [2]. A limitation of the approach is sensitivity to environmental variables. Wind speed above 15 km/h and direct sunlight on the feet can shift surface temperatures by 1-3 °C, potentially pushing healthy feet above the threshold or suppressing the signal from mildly affected feet [10]. Our protocol mitigated this by imaging under a covered race and requiring a 15-minute pen acclimatisation, but these controls may not be feasible on every farm.

Conclusion

The main contribution of this research is a field-validated thermographic screening protocol for early foot rot detection in pastoral sheep, supported by the largest ovine IRT dataset published to date (6,214 paired thermographic-clinical observations from 620 ewes over seven months). The protocol identifies a coronary band maximum temperature threshold of 31 °C as the optimal screening cut-point, delivering a sensitivity of 87.1% well above the 62.8% achieved by conventional visual inspection while maintaining a specificity of 82.4%. Supporting evidence includes the progressive temperature gradient across severity scores, the strong AUC of 0.91, and the 68% capture rate for score 1 cases that were missed by visual inspection on the same day. The interdigital

space and coronary band emerged as the most discriminating anatomical regions, which aligns with the pathogenesis of foot rot as a disease initiated in the interdigital skin. The logistic regression model confirmed that maximum coronary band temperature was the single strongest predictor of foot rot status, with an odds ratio of 2.14 per 1 °C increase (95% CI 1.87-2.44; $p < 0.001$).

For the field of precision livestock management, these results demonstrate that IRT can move from a research curiosity to a practical on-farm tool for sheep lameness monitoring. The combination of high sensitivity, non-contact measurement, and three-fold throughput advantage over manual inspection makes it particularly suited to the extensive pastoral systems of New Zealand, Australia, the United Kingdom, and other temperate sheep-producing regions.

Several questions remain open. First, whether automated real-time temperature extraction using machine-learning algorithms applied to the thermal image stream as sheep move through the race can replace manual ROI definition and bring throughput above 200 sheep per hour has not yet been tested. Second, the optimal re-screening interval for a sequential surveillance programme needs to be determined; fortnightly screening may be more frequent than necessary during low-risk summer months but insufficient during the autumn peak. Third, the interaction between IRT performance and sheep breed has not been explored; heavily woolled breeds may have different baseline foot temperatures than Romney ewes, requiring breed-specific thresholds. Finally, integrating IRT data with accelerometer-based gait analysis another emerging lameness detection technology could yield a multi-modal system with even higher diagnostic accuracy than either method alone.

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Collaborators

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Technical staff

Ms. Rebecca Lawson operated the thermal imaging station during all 14 yarding sessions. Mr. Sam Henare assisted with sheep handling and data recording.

Data and resource providers

The trial was hosted on the commercial property of Doig Farms Ltd. (Canterbury), and the authors gratefully acknowledge the support of farm manager Mr. Grant Doig for providing access to the flock and facilities. Weather data were supplied by the National Institute of Water and Atmospheric Research (NIWA), Christchurch.

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