Detection and Management of Lameness in Dairy Cattle in New Zealand and Tanzania

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Declaration

I hereby declare that I am the sole author of this thesis, entitled: "Detection and management of lameness in dairy cattle in New Zealand and Tanzania", submitted as partial fulfilment of the requirements for the degree of Doctor of Philosophy in Veterinary Science.

This work is the result of my own research, except where otherwise acknowledged, correctly and completely.

Massey University Animal Ethics Committee approved with protocol number 8/22 the studies that required the handling and manipulation of animals.

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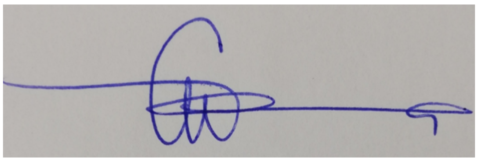

Abstract

Alongside mastitis and infertility, lameness is one of the key animal health challenges on dairy farms. Lameness is particularly challenging due to the complex nature of its aetiopathogenesis and its multiple risk factors. Early detection combined with effective treatment, management and prevention are integral approaches to reducing the impact of lameness on dairy farms, improving productivity, and enhancing animal health and welfare. This thesis focused on improving detection and improved management. Visual locomotion scoring (LS) is currently the most widely used system for detecting lameness worldwide but has attributes that limit its usefulness and application. The first part of this thesis presents three studies looking at alternatives to LS: infrared thermography (IRT) and in-parlour scoring (IPS). IRT was compared to LS in both New Zealand and Tanzania, while IPS was tested in New Zealand alone. Both IRT and IPS proved to be useful alternatives to LS, but further research on more farms across more countries is required before they can replace LS for lameness detection on dairy farms. The second part of the thesis evaluates the response to a three timepoint regime of prophylactic hoof trimming (dry-off, early lactation, and end of lactation) on; 1) lameness incidence and time from calving to increased locomotion score, and 2) the distance from the external claw sole surface to the distal phalanx (DDP), and how this relates to lameness risk. On the study farm, prophylactic hoof trimming did not decrease lameness incidence or time to clinical lameness (locomotion scores ≥2). However, it did increase the interval from calving to an observable change in gait (locomotion scores ≥1). In regard to DDP, the study showed that DDP was not affected by trimming and that changes in DDP did not affect the hazard of increased locomotion score, i.e. either locomotion scores ≥1 or locomotion scores ≥2.

Keywords: lameness; locomotion scoring; infrared thermography; in-parlour scoring; prophylactic hoof trimming; dairy cattle; pasture-based system; tropical

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Foreword

Tanzania ranks third in Africa for cattle population, with approximately 28 million. Most of the cattle are indigenous breeds, including Boran and Tanzanian shorthorn zebu, and approximately 3% of exotic breeds. However, the livestock sector is underperforming, and its contribution to the country's gross domestic product (GDP) is low (7.1%). I have grown up in a pastoral community. I have been with livestock since childhood before I could even go to school for primary education. So, I started witnessing animals' challenges before exactly knowing the issues. Luckily, I ended up in veterinary school, and during those good five years, I realised what I had been seeing since childhood. It was one of the key motives that motivated me to work hard so that I could help those animals back home and elsewhere at large. Most of the families in Tanzania, especially in rural areas, do keep livestock, including cattle, but they do not get maximum benefits from those cattle. For example, as of now, most Tanzanians do not even drink milk, not because they do not like milk, but because there is not enough milk.

Milk consumption in Tanzania averages 47 litres per capita per year, indicating that per capita milk consumption is below the recommended average of 0.5 litres per day. However, currently, there are some initiatives for awareness creation on milk consumption among communities, such as providing milk at schools. However, still, there is not enough milk to meet the demand in Tanzania, with a population of around 60 million. One of the key reasons is the low production and performance of the Tanzanian dairy industry. This underperformance was one of the motives for this PhD project, particularly to study in New Zealand, a famous country in dairy production. Again, I was lucky to meet Professor Richard Laven, who accepted to supervise my PhD research project at Massey University. My dreams and ambitions have come true as the knowledge and skills obtained through this PhD project will help to develop my career. Therefore, after this PhD journey, a new one is starting back home, and acquired knowledge and skills will be instrumental in impacting the livestock sector in Tanzania.

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Key Abbreviations

AHDB	Agriculture and Horticulture Development Board
CHDL	Claw Horn Disruption Lesion
DDP	Distance to the Distal Phalanx
FLIR	Forward Looking InfraRed
FMD	Foot-and-Mouth Disease
FST	Foot Skin Temperature
GDP	Gross Domestic Product
IPS	In-parlour Scoring
IRT	Infrared Thermography
LS	Locomotion Scoring
SLS	Stall Lameness Scoring
US	Ultrasound
VIF	Variance Inflation Factors

Thesis outline and publications

This thesis has been prepared partly via publication. Thus, chapters 1, 2, 8, and 9 were not written for publication. However, chapters 3 to 7 were written for publication, and chapters 3 and 4 have been published, while chapters 5 to 7 are ready for submission.

Table 1. 1:Thesis outline and publications

Chapter	Publication/Write-up	Status
Chapter One: General Introduction	1.0 Background 1.1 Thesis objectives 1.2 Importance of the thesis	Not written for publication
Chapter Two: Literature Review	2.0 Lameness definition 2.1 Causes of lameness 2.2 Risk factors of lameness 2.3 Lameness detection methods 2.4 Prevention and control of lameness	Not written for publication
Chapter Three: Evaluating Alternatives to Locomotion Scoring for Lameness Detection in Pasture-Based Dairy Cows in New Zealand: Infra-Red Thermography	Werema CW, Laven L, Mueller K, Laven R. Evaluating Alternatives to Locomotion Scoring for Lameness Detection in Pasture-Based Dairy Cows in New Zealand: Infra-Red Thermography. *Animals* 11, 3473, 2021: https://doi.org/10.3390/ ani12060703	Published (December 2021)
Chapter Four: Evaluating Alternatives to Locomotion Scoring for Detecting Lameness in Pasture-Based Dairy Cattle in New Zealand: In-Parlour Scoring	Werema CW, Yang DA, Laven LJ, Mueller KR, Laven RA. Evaluating Alternatives to Locomotion Scoring for Detecting Lameness in Pasture-Based Dairy Cattle in New Zealand: In-Parlour Scoring. *Animals* 12, 703, 2022: https://doi.org/10.3390/ ani12060703.	Published (March 2022)
Chapter Five: Assessing Alternatives to Locomotion Scoring for Detecting Lameness in Dairy Cattle in Tanzania: Infrared Thermography	Werema CW, Laven L, Mueller K, Laven R. Assessing alternatives to locomotion scoring for detecting lameness in dairy cattle in Tanzania: Infrared thermography	Submitted to Tropical Animal Health and Production Journal

Chapter Six: Investigating the effect of prophylactic claw trimming on lameness in pasture-based dairy cows.	Werema CW, Hoekstra F, Laven LJ, Mueller KR, Gifford D, Laven RA. Investigating the effect of prophylactic claw trimming on lameness in pasture-based dairy cows.	Submitted to New Zealand Veterinary Journal
Chapter Seven: Evaluating the effect of preventative trimming on distance from the sole surface to the distal phalanx using ultrasonography for lameness prevention in pasture-based dairy cows.	Werema CW, Laven LJ, Mueller KR, Laven RA. Evaluating the effect of preventative trimming on distance from the sole surface to the distal phalanx using ultrasonography for lameness prevention in pasture-based dairy cows.	Submitted to Veterinary Sciences
Chapter Eight: General Discussion	Comparisons of the findings with results from previous studies, limitations, and possible mitigations	Not written for publication
Chapter Nine: Future Studies and Conclusions	Recommended future studies and main conclusions	Not written for publication
References	List of references from chapters not written for publication and ready for submission	

Other publications

List of conference papers and posters

1. *Werema CW, Laven LJ, Mueller KR, Laven RA., 2019. The potential of infrared thermography for the detection of dairy cattle lameness. 20th International Symposium and 12th International Conference on Lameness in Ruminants, Tokyo, Japan.
2. Werema CW, Laven LJ, Mueller KR, Laven RA., 2019. In-shed screening technique for detection of lameness in a pasture-based dairy herd. 20th International Symposium and 12th International Conference on Lameness in Ruminants, Tokyo, Japan.

* Oral presentation

Chapter One: General Introduction

1.0 Background Information

The livestock industry has enormous potential for improving the livelihoods of societies worldwide (McDermott *et al.* 2010; Herrero *et al.* 2013). In rural areas, particularly in developing countries, livestock is an essential asset equivalent to money in the bank, as animals can be sold to obtain cash for different purposes, such as school fees, medical care, food, and during an emergency (Herrero *et al.* 2013). On the other hand, livestock can create adverse effects, including soil erosion, climate change, and conflicts between crop farmers and cattle herders (Uddin and Kebreab 2020). For instance, there have been reports of conflicts between crop farmers and livestock herders in the tropics, with intense fights resulting in the killing of human beings and animals (Benjaminsen *et al.* 2009; Butler and Gates 2012). Nevertheless, with global food demand rising, livestock products form a reliable food source (Delgado 2003; Freidberg and Freidberg 2009). As a result, global food demand is driving remarkable growth in the livestock industry, with a global emphasis on increasing production and processing.

Cattle farmers can utilise natural pastures, roughages, and family members as labourers, as well as relatively simple animal shelters; these features make farming cattle more manageable than other domestic animals (McDermott *et al.* 2010). As a result, globally, a large range of cattle breeds exist (Porter 2002), which are classified based on their purpose, e.g. beef, dairy, and multi-purpose (milk, meat, draught animal power). These diverse types of cattle are suited to different production systems. For example, the popular dairy breeds in New Zealand include Friesian, Jersey, Ayrshire, and their crosses (Buckley *et al.* 2014). While the same breeds and crosses are utilised in Tanzania, they are also crossed with indigenous cattle breeds such as Boran and Zebu to improve animal resistance to harsh Tanzanian conditions such as heat stress and tickborne diseases (Keyyu *et al.* 2006; Nkya *et al.* 2007).

Primary dairy production includes intensive and extensive systems. Extensive dairy systems are characterised by large areas of natural pasture, free-range animals, low input of insecticides, drugs, feedstuffs, and low production levels (Seré *et al.* 1996; Robinson *et al.* 2011). Extensive systems are often thought to be superior in terms of welfare as the lack of confinement means cattle are generally able to express their natural behaviours, though welfare outcomes may not be so clear (Mee and Boyle 2020). Organic dairy farming systems have been developed to address public concerns regarding environmental 'pollution' by chemicals used on farms. Organic farming focuses on environmental protection, which is associated with reduced pollution and nutrient loss at the farm level (Thomassen *et al.* 2008). However, it requires more farmland as it restricts feed imports and encourages mixed farming (Cederberg and Mattsson 2000). One advantage of the organic system is that it tends to have lower disease prevalence, including lameness, probably because organic farms tend to be more extensive than non-organic ones (Dippel *et al.* 2009).

In contrast, high stocking density, diets high in grain concentrates, high use of veterinary pharmaceuticals and high production characterise intensive dairy production (Thomassen *et al.* 2008; Cook *et al.* 2016). Such systems provide increased output per cow but rely on more advanced technologies (Britt *et al.* 2021). In Tanzania, there is currently a drive towards livestock modernisation and an emphasis on intensive production with the aim of improving productivity alongside a reduction in the number of cattle (MLFD 2015, 2019). Intensive dairy production systems are linked to environmental pollution and climate change (Thomassen *et al.* 2008; Uddin and Kebreab 2020), as well as disease and animal welfare issues (Laven and Holmes 2008; Whay and Shearer 2017).

Globally the top three diseases in the dairy industry, all of which result in significant economic losses and animal welfare issues on dairy farms, are mastitis, infertility, and lameness (Enting *et al.* 1997; Green *et al.* 2014; Whay and Shearer 2017). Compared to lameness, both mastitis and infertility have been studied more extensively. For example, Laven (2012) reported searching peer-reviewed publications using the keywords ‘cattle’ and ‘lameness’ on the Scopus search engine and finding 1073 articles, but when he replaced lameness with fertility and mastitis, he found 4867 and 7346 articles, respectively.

Thus compared to mastitis and infertility, lameness is under-researched. When we look at where that research has been undertaken, the vast majority has been undertaken in the Northern Hemisphere, particularly in Western Europe and North America (Laven 2019). However, there is much less published research from pasture-based production systems, such as in New Zealand, and the situation is worse in developing countries like Tanzania.

Lameness is a complex condition characterised by an observable change in gait and posture, which is associated with pain in, or injury to, the musculoskeletal system (Olechnowicz and Jaskowski 2011; Ghotoorlar *et al.* 2012). It is one of the most challenging conditions to treat and manage due to its multifactorial nature, especially in relation to its aetiopathogenesis (Garvey 2022).

One clear thing from the existing literature is that early detection and timely and effective treatment are key to the prevention and control of lameness (Leach *et al.* 2012; Thomas *et al.* 2016). In order to achieve this, we need an effective and systematic method of detecting lame cows. Currently, manual locomotion scoring is the most widely used method. However, it has several limitations, including being time-consuming and subjective. Numerous different locomotion scoring systems have been described in the literature, each with its own advantages and disadvantages (Schlageter-Tello *et al.* 2014). There is thus no consensus on which system is optimal; indeed, there is probably no single optimal system.

One particular issue, especially in pasture-based production systems where locomotion scoring is undertaken after milking and cows are scored walking along wide tracks rather than through narrow passageways, is individual identification of lame cows (particularly mildly lame ones). This challenge is exacerbated by the rate at which cows exit the milking parlour, especially in herringbone parlours, where they leave as a bunched group. Environmental factors such as sunlight, rain, and wind (Fabian *et al.* 2014; Ranjbar *et al.* 2016; Werema *et al.* 2021) can also interfere with the scoring process. Thus, especially in large pasture-based farms, we need effective but simple alternatives to locomotion scoring for the early identification of lame cows.

Another key issue is the need for training. In developing countries like Tanzania, knowledge and skills regarding lameness are limited, and routine lameness detection and prevention procedures are rarely undertaken, increasing the impact of lameness on productivity and its potential to produce substantial animal welfare problems (Kashoma et al. 2015; Mwaipopo and Mbaga 2022). This lack of knowledge and skills is particularly important when looking at LS (locomotion scoring), where it is clear that to be effective, it needs to be undertaken by trained observers, as without training, there can be very high between and within-observer variation in recorded scores (Schlageter-Tello et al. 2014, 2015; Ramanoon et al. 2018). A relatively high level of training is achievable in commercial dairy systems, especially where farms are large and employ professional staff. In countries where farms are smaller and semi-commercial and the training infrastructure limited, e.g. Tanzania, the requirement that observers are trained is likely to limit the use of LS even if farmer awareness of LS is improved. Alternatives to LS, which are less subjective and thus do not require training, are needed in such systems.

Early detection is an important part of reducing lameness prevalence but needs to be part of a comprehensive package of lameness prevention measures to be truly effective. In the Northern and Southern hemispheres, much work has been done in controlling infectious causes of lameness, such as digital dermatitis, through biosecurity programs on the farm and improving hygiene (Laven and Hunt 2002; Evans *et al.* 2016; Solano *et al.* 2017). In contrast, the prevention and control of non-infectious causes of lameness remain a great challenge (Potterton *et al.* 2012). Multiple studies have reported the beneficial effects of prophylactic hoof trimming regarding lameness prevention (Manske *et al.* 2002; Groenevelt *et al.* 2014; Van Hertem *et al.* 2014). However, preventative hoof trimming still has many unanswered questions regarding its efficacy, including timing and frequency of trimming (Pedersen *et al.* 2022).

One key area where research is limited is the value of trimming in cattle that are permanently based at pasture (as is standard practice in New Zealand), with only one published study on prophylactic hoof trimming as a lameness prevention strategy in such systems (Bryan *et al.* 2012). As a result, in such countries, lameness can have low returns. Therefore, more studies are needed to understand the impact of this lameness prevention measure on cattle kept permanently in pasturelands like in New Zealand.

1.1 Thesis Objectives

The objectives of this thesis were to:

1. Investigate alternatives to locomotion scoring for the detection of lameness in dairy cattle in New Zealand and Tanzania,
2. Evaluate the impact of prophylactic hoof trimming as a preventative measure of lameness in pasture-based cows in New Zealand, and
3. Assess the effect of preventative hoof trimming on claw sole thickness for lameness prevention in dairy cows kept permanently at pasture in New Zealand.

1.2 Importance of this Thesis

Lameness is a complex multifactorial problem resulting in severe economic losses and a major impact on animal welfare. Thus, early detection, timely and effective treatment and appropriate prevention and control strategies are essential. The information generated in this thesis will contribute to knowledge and skills for lameness detection, prevention, and management in dairy cattle, improving the dairy industry in New Zealand and Tanzania.

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Chapter Two: Literature Review

2.0 Introduction

This review will consist of two main parts 1) lameness detection techniques and 2) lameness prevention and control strategies in dairy cattle.

2.1 Lameness Definition, Risk Factors, and Detection Methods

Lameness is a multifactorial and complex condition characterised by a change of gait and posture from pain due to musculoskeletal dysfunction or inflammation (Olechnowicz and Jaskowski 2011; Ghotoorlar *et al.* 2012). Lameness can be classified as either acute or chronic based on the onset, severity, response to treatment, and recovery duration. Acute lameness denotes a condition that has occurred for a short time, i.e., from hours to a few days, while chronic lameness has a prolonged duration, i.e., weeks, months or even years (O'Callaghan 2002; O'Callaghan *et al.* 2003). Both acute and chronic lameness can occur in the same dairy herd.

The pain and discomfort associated with lameness pose a significant animal welfare problem (Laven and Holmes 2008; Whay and Shearer 2017). In cattle, lameness has severe negative impacts on production (Warnick *et al.* 2001; Green *et al.* 2002; Archer *et al.* 2010), reduces reproductive performance and longevity (Booth *et al.* 2004; Machado *et al.* 2010; Somers *et al.* 2015), as well as decreasing animal welfare (Laven and Holmes 2008; Whay and Shearer 2017). To meet the increasing global demand for milk and milk products (Delgado 2003; Herrero *et al.* 2013) whilst also improving efficiency and productivity, means we have to tackle the key animal health challenges facing the dairy industry: mastitis, infertility, and lameness. Of those diseases, lameness is currently regarded as the hardest challenge because of its complex nature (Afonso *et al.* 2020).

2.1.1 Causes of Lameness in Dairy Cattle

More than 90% of lesions/diseases causing lameness are encountered in the foot (Clarkson *et al.* 1996). Among feet, hindlimbs are the most commonly affected, accounting for about 92% of lameness cases in housed cattle (Murray *et al.* 1996) and 67% in cattle kept permanently at pasture (Chesterton *et al.* 2008). Causes of lameness can be broadly classified into two groups: infectious and non-infectious causes, with non-infectious claw horn lesions/diseases being considered the main challenge to reducing lameness in dairy cattle (Murray *et al.* 1996; Potterton *et al.* 2012; Shearer *et al.* 2015).

2.1.1 Infectious Causes

The key infectious diseases leading to lameness in dairy cattle are summarised in Table 2.1. Infectious causes include bacterial diseases, such as foot rot caused by *Fusobacterium necrophorum* (Checkley *et al.* 2005), which produces necrosis of the interdigital skin resulting in severe lameness if not treated, and digital dermatitis, associated with *Treponema spp.,* which produces erosive and proliferative lesions of the digital skin (Laven and Logue 2006; Evans *et al.* 2016), as well as viral infections, such as Foot and Mouth Disease (FMD), which produces lameness secondary to the production of sores and blisters (Rainwater-Lovett *et al.* 2009).

Table 2.1: Key infectious claw lesions and diseases that lead to lameness in dairy cows (Checkley *et al*. 2005; Rainwater-Lovett *et al.* 2009; Potterton *et al.* 2012; Evans *et al.* 2016).

S/N	Lesion or Disease	Brief description
1	Digital Dermatitis (DD)	An erosive infection of the skin; typical clinical signs are associated with the presence of *Treponema spp.*
2	Interdigital Dermatitis	An infection of the skin between the digits that do not involve the deep tissues. Mixed infection with *Dichelobacter nodosus is* commonly found.
3	Interdigital Necrobacillosis (Foot rot)	A bacterial disease caused by *Fusobacterium necrophorum.*

4	Heel Erosion	An erosion of the heel tissue, which can be irregular depressions or V-shaped grooves. In severe cases, the heel becomes sore, consequently instability of the claw. Mixed infection with no definitively identified cause.
5	Foot and Mouth Disease (FMD)	A viral disease caused by FMDV of Picornaviridae family affects cloven-hooved animals. The clinical signs include fever, blisters in feet and mouth, once blisters rapture, results in lameness

2.1.2 Non-infectious Causes

Non-infectious lameness is principally caused by claw horn disruption lesions (CHDL). CHDL account for approximately 65% of lameness cases in housed cows where digital dermatitis is present (Murray *et al.* 1996; Bicalho and Oikonomou 2013) and about 72.5% in pasture-based cows in New Zealand where digital dermatitis is very rare (Chesterton *et al.* 2008). The most common non-infectious claw lesions and diseases causing lameness cases in dairy cows are summarised in Table 2.2. Furthermore, reviews by both (Potterton *et al.* 2012; Bicalho and Oikonomou 2013) reported that white line disease, sole haemorrhages, and ulcerations are the most common claw lesions inducing lameness in dairy herds.

Table 2.2: Most common non-infectious claw lesions and diseases that lead to lameness in dairy cows (Blowey and Weaver 2011; Potterton *et al.* 2012; Shearer and van Amstel 2017).

S/N	**Lesion or Disease**	**Brief description**
1	White Line Disease (WLD)	A group of diseases occurs at the junction between the wall and the sole, ranging from haemorrhage to abscessation via separation.
2	Sole Haemorrhage	Bleeding from the corium into the hoof horn tissue.
3	Sole Ulcers	An area of damaged sole horn which has completely lost the overlying horn exposing the underlying corium. Usually found near the sole/heel junction.

4	Toe Ulcer/Abscess	Damage to the cranial area of the sole either with exposure of the corium (ulcer) or collection of pus between the horn and the corium (abscess).
5	Thin Sole	Excessive loss of sole horn leads to soft, pliable soles, which are highly prone to injury. Usually, the result of excessive wear or over trimming.
6	Corkscrew Claw	Irregular growth of the claw with rotation of the toe.
7	Hoof horn fissures	Horizontal or vertical cracks in the wall horn. These result from disruption of hoof horn production (horizontal fissures) and perhaps excess forces on the hoof horn (vertical fissures).
8	Foreign Bodies	Penetration of the hoof, usually the sole, by foreign bodies, e.g. nails, grit from palm kernel extract and teeth.
9	Interdigital Hyperplasia	Overgrowth of /tissue between the digits, resulting in a firm mass resembling a tumour. Secondary bacterial infection is common.

2.1.2.1 Pathogenesis of the Claw Horn Disruption Lesions

Much of the literature on the aetiopathogenesis of CHDL has focused on it occurring after the development of laminitis, with subacute ruminal acidosis being identified as a key cause of laminitis (Nocek 1997; Vermunt and Parkinson 2002; Cook *et al.* 2004). However, this assertion has been challenged in recent years, with the role of nutrition in CHDL being recognised as less important (Newsome *et al.* 2016). One fundamental change has been the change to describing the underlying lesion as coriosis (degeneration of the corium) instead of laminitis (inflammation of the laminae), as it is the corium that is disrupted during the development of CHDL, not the laminae (Blowey and Weaver 2011).

This coriosis is associated with increased internal pressure from the distal phalanx (Ossent and Lischer 1998; Blowey and Weaver 2011). This pressure is related to load bearing in the feet. Van der Tol *et al.* (2004) demonstrated uneven weight-bearing within the foot, with the lateral claw carrying 80% and the medial claw 20% in the non-trimmed foot. This is reflected in the appearance of CHDL, with the lateral claw of the hindlimb being much more commonly affected by CHDL than the medial one (Le Fevre *et al.* 2001; Nikkhah *et al.* 2005; Chesterton *et al.* 2008). It is now increasingly recognised that the pathogenesis of the key CHDL lesions, sole haemorrhage, sole ulceration and white line disease, is primarily linked to pressure load and the distal phalanx.

In cattle, the laminae are not so extensively interdigitated as in horses, and the area of attachment to the distal phalanx is smaller (Räber *et al.* 2004). The axial aspect of the distal phalanx is arched over its ventral surface so that a cow's weight is carried at its heel and toe zones and along the abaxial wall. This places particular stress on the area of the hoof near the posterior projection of the distal phalanx (the flexor tuberosity) - this is the position of the typical sole ulcer site. The important structures reducing the pressure of the distal phalanx on the corium are the digital cushion and the suspensory apparatus. The function of the digital cushion is to cushion and dissipate the forces from the distal phalanx within the bovine claw horn capsule. The digital cushion has three columns of adipose tissue running longitudinally from the heel to the apex of the distal phalanx, i.e. axial, abaxial and middle-fat pads (Räber *et al.* 2004; Räber *et al.* 2006). These fat pads are linked by connective tissues to form a stable cushion. The middle fat pad ends at the apical end of the flexor tuberosity of the distal phalanx, which may mean that there is less cushioning in this area, consequently increasing the likelihood of sole ulceration (Räber *et al.* 2004).

Digital cushions vary significantly between animals. For example, Räber *et al.* (2006) demonstrated that the digital cushions of cows in their second or third parity had more fat than those of heifers and that those of cows in their ≥4 parity had more connective tissue than those of their younger peers. The factors causing these differences are unclear. Initial reports suggested that digital cushion thickness varied with body condition (i.e. body fat percentage); however, Newsome *et al.* (2017a) demonstrated that this link was not as strong as previously suggested and that the thinning of the digital cushion was directly related to calving. They suggested that the thinning of the digital cushion may actually be related to the change in the integrity of the suspensory apparatus which occurs prior to calving because of the changes in collagen integrity required to prepare the cow for calving (Webster 2001; Tarlton *et al.* 2002; Knott *et al.* 2007).

This loss of suspensory apparatus integrity around calving is a crucial part of the development of CHDL. The link between parturition and CHDL was demonstrated in a series of papers from the University of Bristol group (Webster 2001; Tarlton *et al.* 2002; Knott *et al.* 2007). As part of the process of preparing for parturition, hormonal changes principally increase estrogen and cause the relaxation of collagen-containing tissues such as ligaments, tendons and connective tissues throughout the body of the cow, including the suspensory apparatus of the distal phalanx (Webster 2001; Tarlton *et al.* 2002; Knott *et al.* 2007). This results in increased movement of the phalanx within the claw horn capsule and, potentially, displacement (i.e. sinking) and rotation of the distal phalanx. If the movement is sufficient, the result is damage to the corium as the distal phalanx pushes against it. This damage is seen as hoof horn haemorrhages or 'bruises' on the horn surface once the horn made in this period has reached that surface as part of the normal growth and wear cycle (Leach *et al.* 1997). This process takes one to two months, depending on the balance between growth and wear. Hoof horn haemorrhages are the precursor lesions to the more severe lesions of white line disease and toe/sole ulcers.

Sole ulcers typically occur at the site of the flexor tuberosity of the distal phalanx (Blowey 2004) and occur when the damage at that site is severe enough to stop horn formation. This is typically when there is an excessive load on the hoof during the period of time when the integrity of the suspensor apparatus is reduced (leading to increased movement or sinking of the distal phalanx), especially if the excess load occurs over a prolonged period of time (Ossent and Lischer 1998; Blowey and Weaver 2011). Toe ulcers, which are significantly less common, occur when the apex of the distal phalanx damages the corium (Van Amstel and Shearer 2008).

White line disease results from a similar process of corium damage. The white line, which links the sole horn to the wall horn, consists of interdigitating horn produced by the sole corium and laminar horn leaflet cells produced by the laminar corium (Kempson and Logue 1993). The sole corium producing the interdigitating horn is damaged by lateral movement of the distal phalanx rather than the up-down movement, which produces the sole ulcer (Ossent and Lischer 1998; Blowey and Weaver 2011). If this damage is severe enough, the sole and wall begin to separate, producing white line separation. The white line can then become impacted with foreign material (increasing the degree of separation, which allows in more material). If the material becomes trapped in the white line, an infection can develop, producing a white line abscess.

As discussed earlier, CHDLs are usually seen in the hind limbs despite hind limbs bearing less of the bodyweight than the forelimbs (Van der Tol *et al.* 2004). This may, in part, be due to the rigid structure of the hindquarters (limbs connected to the pelvis by ball and socket joints) compared to the more flexible structure of the forequarters, where the front legs are attached to the shoulders via ligaments and tendons (Shearer 1997; Shearer and van Amstel 2001; Franck and De Belie 2006). Another possible explanation is that during late pregnancy and lactation, the calf in utero and udder increases the weight on the rear legs, creating more pressure, and the increased size of the udder occupies more space forcing cows to abduct their hind limbs, resulting in stress to the lateral claws (Chapinal *et al.* 2009; Shearer *et al.* 2015).

CHDL development is linked to numerous factors, with pressure on the distal phalanx leading to contusions of the corium as the initial stage of CHDL development. However, the pressure effect is exacerbated by physiological changes in the periparturient period, i.e. increased laxity and reduced strength of the suspensory apparatus, as well as alterations in the composition and thickness of the digital cushion.

2.1.2 Risk Factors Influencing Lameness in Dairy Cattle

2.1.2.1 Environmental and Managemental Risk Factors

The surrounding environment and infrastructure of the farm can influence lameness by changing the risk of foot injuries and influencing horn wear (Chesterton *et al.* 1989; Cook and Nordlund 2009; Barker *et al.* 2010). The housing environment is an extremely important lameness risk factor for housed cattle. Concrete floors, whether for walking or lying on, are associated with an increased prevalence of claw lesions compared to other floor types, such as rubber floors or bedded surfaces with straw or sand (Bergsten and Frank 1996; Webster 2001; Cook *et al.* 2004; Cook and Nordlund 2009; Ouweltjes *et al.* 2009). For example, Ouweltjes *et al.* (2009) reported that cows kept on concrete floors had higher levels of sole haemorrhages (48% versus 22% of those kept on rubberised floors). Keeping cows at pasture permanently probably reduces lameness risk (Laven and Holmes 2008; Fabian *et al.* 2014), and in housed cows, access to pasture has been shown to reduce rates of CHDL (Hernandez-Mendo *et al.* 2007; Sadiq *et al.* 2021b).

Other environmental factors related to lameness include stocking density in both housing and collecting yards prior to milking (Chesterton *et al.* 1989; Chesterton 2004; Cook and Nordlund 2009), and walking distance and trackway quality (McDermott *et al.* 2010;

Burow *et al.* 2014). Increased moisture in the environment has been associated with severe outbreaks of lameness in both housed and cows kept primarily at pasture but exposed to wet concrete collecting yards (van Amstel *et al.* 2004; Sanders *et al.* 2009; Mason *et al.* 2012).

Management of cows is important. Poor cow handling, especially prior to milking, increases lameness risk as it impacts cow behaviour (Chesterton *et al.* 1989; Galindo and Broom 2000). Perhaps the most important management tool, especially in housed cows, is the use of routine claw trimming, which has been reported to reduce lameness prevalence in housed cattle (Manson and Leaver 1988a; Manske *et al.* 2002; Hernandez *et al.* 2007), probably through helping to maintain the claw shape and balance weight-bearing between claws (Toussaint Raven 1985; Shearer and van Amstel 2001; Van der Tol *et al.* 2004).

2.1.2.2 Nutritional Causes

Diet can directly impact horn quality (Vermunt and Greenough 1995; Santos and Overton 2001) and lesion healing (Lischer *et al.* 2002; Wilde 2006). Both zinc and biotin supplementation has been suggested to strengthen the hoof by regulating and activating keratin protein production in the claw (Wilde 2006; Green *et al.* 2014).

Insufficient feeding, either low or poor feed quality, can lead to loss of body condition, which is a risk factor for lameness, at least in housed dairy cows (Green *et al.* 2014; Lim *et al.* 2015; Randall *et al.* 2015). As discussed earlier, it was thought that this association was a simple association between body condition and digital cushion thickness, but the findings by Newsome *et al.* (2017a) suggest that the association between body condition and digital cushion thickness (and thus lameness) is more complex involving multiple factors, such as physiological changes around periparturient period. Nevertheless, what is clear is that lameness leads to low body condition. Lame cows have increased lying times, decreased feeding times and feed intakes, as well as reduced rumination times, all of which can lead to low body condition scores (Alsaaod *et al.* 2012; Van Hertem *et al.* 2014; Hut *et al.* 2021).

2.1.2.3 Cow-level Factors

A cow's production and reproduction status can influence lameness risk. Lameness risk varies across physiological stages such as pregnancy, calving, and lactation (Chapinal *et al.* 2009; Newsome *et al.* 2017b), as well as age and parity (Mason 2017). Genetics is also important, with a large difference between breeds. Holstein Friesians have a much higher risk of lameness (Chesterton *et al.* 1989; Vermunt and Greenough 1995; Somers *et al.* 2003). Within the Holstein Friesian breed, there is a strong association between the foot and limb conformation (which have a relatively high heritability) and lameness risk (Wells *et al.* 1993; Boettcher *et al.* 1998; Winters 2015). For example, Wells *et al.* (1993) found that low claw angle was associated with lameness, while Boettcher *et al.* (1998) reported that cow-hocked posture and wide rumps were linked to lameness prevalence.

2.2 Methods and Procedures for Lameness Detection in Dairy Cattle

Early lameness detection is challenging, but delayed diagnosis and treatment of lameness can result in irreversible claw lesions, such as the formation of bone exostoses on the distal phalanx (Newsome *et al*. 2016). Once such lesions develop, a vicious cycle of lameness events can then occur.

Numerous systems are described in the literature for the detection of lameness in dairy cows. These systems vary from those employed at the individual level (like is this cow lame?), e.g. use of hoof testers (Desrochers *et al.* 2001), and at the herd level (which of these cows are lame?), e.g. scoring systems in moving (Schlageter-Tello *et al.* 2014), or standing cows (Leach *et al.* 2009; Gibbons *et al.* 2014; Palacio *et al.* 2017). Individual assessments can be applied at the herd level; routine hoof trimming of a herd provides a useful screening opportunity for diagnosing and treating individuals and recognising herd issues (Stoddard and Cramer 2017), using a test that is different from locomotion scoring.

Each evaluation process has its own advantages and disadvantages. There is no definitive method that provides 100% sensitivity and specificity, and the method selected must consider the production system, herd size and environment in which it is to be used. Several studies have reported that locomotion scoring systems lack sufficient sensitivity and specificity, e.g. (O'Callaghan 2002; Flower and Weary 2006, 2009). Furthermore, locomotion scoring systems have limited applications, particularly in pasture-based systems (Fabian *et al.* 2014; Ranjbar *et al.* 2016; Werema *et al.* 2022). The advantages and challenges of different lameness detection methods are outlined below.

2.2.1 Physical Examination and Use of Hoof Testers

Traditional clinical examination of the hoof still has an important role to play in the diagnosis of lameness. Lifting of the foot to examine and explore the claws and the use of digital pressure or hoof testers to locate the painful area, alongside therapeutic trimming, are still the mainstay of treatment (Desrochers *et al.* 2001; Nelson *et al.* 2022). However, clinical examination of the claws requires trained personnel and handling facilities. While still widely used and dependable at the individual cow level (Nelson *et al.* 2022), individual lifting of the claws is not an efficient lameness detection method, especially in large herds, where it would be time-consuming, labour intensive and involve the risk of injury to both animals and veterinarians for no gain in animals with no lameness or claw abnormalities.

2.2.2 Locomotion Scoring

Locomotion scoring (LS) is a system of gait assessment of an individual animal or whole herd. The intention of LS is to identify lame cows that need further examination and treatment based on detected abnormalities in a cow's gait. LS is widely used and currently regarded as a benchmark for detecting lameness in dairy farms (Schlageter-Tello *et al.* 2014). Two main system types exist, manual (visual) locomotion scoring (MLS) by a human observer and automatic locomotion scoring (ALS) (using sensor technology). At present, MLS is much more common than ALS, at least in part because of the cost of the technology (Schlageter-Tello *et al.* 2014).

2.2.2.1 Manual Locomotion Scoring

Manual locomotion scoring (MLS) systems use visual observations to score cows against stated criteria. MLS was first introduced in the 1980s when dairy cows were scored by observing gait and posture while walking and standing (Manson and Leaver 1988b). Scoring can be undertaken by observing the herd in real-time (Fabian *et al.* 2014; Ranjbar *et al.* 2016; Werema *et al.* 2021) or by viewing recorded videos (Engel *et al.* 2003; Flower and Weary 2006; Tuyttens *et al.* 2009; Alsaaod *et al.* 2017). Schlageter-Tello *et al.* (2015) reported that whether the observation was performed in real-time or on video influenced the identification of a lame cow much less than the observer. Thus, both real-time and video observation seem to be acceptable for locomotion scoring and lameness evaluation in dairy cattle. However, video evaluation requires high-quality videos and takes as much time as real-time observation, so it is likely to be more expensive.

There are two main MLS systems based on the type of scale applied. In systems with a numerical scale (Manson and Leaver 1988b; Winckler and Willen 2001; Thomsen *et al.* 2008), the observer gives the cow(s) a discrete score based on the assessment of various gait and posture features. A wide range of scales has been used, ranging from a simple two-point scale system (sound or lame) (Groehn *et al.* 1992; Whay 2002) to as many as fourteen points (Offinger *et al.* 2013). The alternative is the use of a continuous visual analogue scale (Engel *et al.* 2003; Flower and Weary 2006; Tuyttens *et al.* 2009), with observers simply recording on a scale how severe they think the lameness is. For example, Flower and Weary (2006) used a 100-unit scale of 0- classified as perfect gait, while 100 was as severely lame as it was possible to be. Continuous scales have not been widely used outside of research, even though they may be more sensitive to changes in gait and posture than discrete scores (Flower and Weary 2006), perhaps because of the inherent increased variability of continuous scale scores (Engel *et al.* 2003).

Thus, the most widely used method of active lameness detection on dairy farms is numerical visual locomotion scoring. Many locomotion scoring systems have been developed for use on the farm; Schlageter-Tello *et al.* (2014) identified 25 different locomotion score systems published in the peer-reviewed literature, with no consensus on the optimal system. These systems all vary in the gait and posture features they include. For example, Manson and Leaver (1988b) included the ability to turn, but Sprecher *et al.* (1997) did not, while the opposite was true of the arching of the back. According to Schlageter-Tello *et al.* (2014), the most commonly cited system is the 5-point (1 to 5) system proposed by Sprecher *et al.* (1997). While this system has been used in New Zealand (Alawneh *et al.* 2012b), the current industry standard scheme is a 4-point (0 to 3) system based on the Agriculture and Horticulture Development Board (AHDB) mobility score, which was developed in the UK (Fabian *et al.* 2014).

One key issue with MLS is the assumption that all cows in a herd walk in the same way, so the same changes indicate lameness. However, animal factors such as age (older animals), parity, pregnancy and lactation stage all change gait and posture, so they should ideally be taken into account when scoring (Flower and Weary 2009; Van Nuffel et al. 2016). This is extremely difficult to achieve, especially when observing cows walking back to a paddock after milking. The most fundamental problem with LS is its subjective nature, with relatively high within- and between-observer variation. Schlageter-Tello *et al.* (2014) found that in peer-reviewed reports, inter-observer agreement ranged from 17 to 95%. They reported that increasing the number of categories decreased the percentage of agreement, with the lowest percentage of the agreement being recorded with the nine-point system (17 to 47%) and the highest with the two point system (83-97%), indicating that the observer has a significant influence on MLS scores (Engel *et al.* 2003; Channon *et al.* 2009). The effect of the observer is increased when training is limited (Schlageter-Tello *et al.* 2014, 2015; Ramanoon *et al.* 2018).

Visual locomotion scoring is time-consuming and can require significant labour resources, especially in larger herds. In pasture-based dairies where scoring is usually undertaken after milking (Fabian *et al.* 2014), the rate at which cows exit the milking parlour can add significant difficulties in identifying individual cows while locomotion scoring. To mitigate this, Ranjbar *et al.* (2016), who investigated risk factors for lameness in Australian dairy herds, recorded locomotion scores as a tally instead of at the individual cow level. However, while this can help determine the herd prevalence, it does not help identify individual cows requiring treatment. Additionally, where locomotion scoring is undertaken, outside factors such as sunlight, wind, and rain can also hinder locomotion scoring (Fabian *et al.* 2014).

2.2.2.2 Automatic Locomotion Scoring

Automatic locomotion scoring (ALS) systems employ sensor technology to record changes in cow behaviour or production variables linked to lameness. The dominant systems include data loggers attached to animals, walk-overs sensors, and cameras (Rutten *et al.* 2013; Schlageter-Tello *et al.* 2014; Van Nuffel *et al.* 2015). The most used sensors are force plates, pressure-sensitive walkways, accelerometers, and pedometers (Maertens *et al.* 2011; Thorup *et al.* 2015; Van De Gucht *et al.* 2017).

Schlageter-Tello *et al.* (2014) reported that 15 different ALS had been described in the literature. These ALS systems could be classified according to three main approaches: kinetics, kinematics and indirect. The kinetics and kinematics approaches mimic the MLS systems by measuring gait and back posture variables. Kinetic techniques utilise force plates and balance-weighing machines to get force measurements (Flower *et al.* 2005; Maertens *et al.* 2011; Viazzi *et al.* 2013). The ground reaction force of each limb is the most critical parameter as this plays a significant role in attaining other information such as strength, weight-bearing distribution, velocity, shifting weight, and leg activity (Maertens *et al.* 2011; Ghotoorlar *et al.* 2012; Viazzi *et al.* 2013), and live weight assessment (Alawneh *et al.* 2012a).

Kinematic techniques employ markers, which are commonly placed on the skin above anatomical landmarks, to help monitor the movement of the animal using high-speed cinematography (Flower *et al.* 2005; Ghotoorlar *et al.* 2012; Viazzi *et al.* 2013). Motion analysis software then automatically computes the characteristics of gait and posture, such as swing interval, head position, and stride length (Flower *et al.* 2005; Van Nuffel *et al.* 2013; Viazzi *et al.* 2013).

Indirect approaches employ behavioural and production variables as indicators of impaired locomotion. For example, measured production variables have included body weight and milk yield (Chapinal *et al.* 2009; Miekley *et al.* 2013; Van Hertem *et al.* 2014), while behaviours measured have included lying time, feeding time, and distance walked (Song *et al.* 2008; Poursaberi *et al.* 2010; Viazzi *et al.* 2013). The key challenge of the indirect approach is that the measured parameters are not only affected by lameness but other factors such as oestrus status, diseases such as mastitis and metabolic disease and also farm management (Hogeveen *et al.* 2011; Walsh *et al.* 2011). The general consensus is that current ALS systems are inefficient and costly (Nuffel *et al.* 2015; Van De Gucht *et al.* 2017) and still require well-trained personnel to record and interpret the findings. As a result, ALS is currently not a viable option for routine on-farm lameness detection.

2.2.3 Infrared Thermography

Infrared thermography (IRT) is a non-invasive technique that measures body surface temperature and captures a thermal image of the anatomical region/structure (Eddy *et al.* 2001). The infrared camera absorbs infrared radiation from the imaged animal and produces images obtained from the quantity of heat delivered. Each pixel in the created picture illustrates the recorded surface temperature of the anatomical zone imaged (Alsaaod *et al.* 2015). The thermal images produced can be displayed both in greyscale and colour, where white or red represent the hottest zones, whilst black or blue describe the coldest locations (Eddy *et al.* 2001; Colak *et al.* 2008).

The inflammatory reactions that accompany most diseases and injuries release vasoactive substances and mediators, which increase blood flow to the damaged region - consequently increasing body surface temperatures (Nocek 1997; Shearer 1997). IRT can thus be used to detect the increased temperatures associated with those injuries and diseases (Eddy *et al.* 2001; Schaefer *et al.* 2004; Colak *et al.* 2008). However, body surface temperature can be influenced by other factors than inflammation, including physiological status (Nikkhah *et al.* 2005; Alsaaod and Büscher 2012; Bobić *et al.* 2018), environment and surroundings (Main *et al.* 2012; Landgraf *et al.* 2014), and animal activity level (Gloster *et al.* 2011).

In cattle, IRT has been used for screening dairy cattle for mastitis (Colak *et al.* 2008), Bovine Viral Diarrhoea Virus (Schaefer *et al.* 2004), and Foot and Mouth Disease (FMD) Virus (Rainwater-Lovett *et al.* 2009). It has also shown potential for oestrus detection and prediction of ovulation (Talukder *et al.* 2014). In lame cows, IRT has potential uses in detecting claw lesions as well as monitoring the healing process following treatment (Wood *et al.* 2015). However, whenever IRT is used for lameness detection, its interpretation needs to take into account factors that may influence its results and, if possible, minimise their impact.

LokeshBabu *et al.* (2018) categorised these factors into technological (distance to subject and image repeatability), environmental (ambient temperature, wind, dirt and moisture on floor), and biological (pregnancy, stage of lactation, hair on the subject, activity, and medications). Of these factors, key factors include the stage of lactation (Nikkhah *et al.* 2005) reported mean temperatures that were >5°C higher in cows that were ≤200 days in milk compared to cows which were >200 days in milk; activity (Gloster *et al.* 2011) reported that the hoof temperature of cows that were lying down could be as much as 14°C higher than those of the same cows standing on concrete; ambient temperature (Gloster *et al.* 2011) reported that increasing ambient temperature from 10 to 20°C increased thresholds for FMD detection by 9-10°C, and hoof cleanliness (Stokes *et al.* 2012) reported that the optimal lameness detection threshold increased from 22°C in freshly cleaned feet to 27°C in feet that had not to be cleaned. All of these factors need to be considered when developing IRT as a method for lameness detection as they may complicate interpretation and reduce accuracy.

The optimal site for IRT when detecting lameness is not definitively proven. However, the sites most frequently used by researchers include the plantar aspect of the foot (Main *et al.* 2012; Stokes *et al.* 2012; Wood *et al.* 2015), the coronary band (Nikkhah *et al.* 2005; Alsaaod and Büscher 2012; Alsaaod *et al.* 2014), and zones on the claw sole (Rodríguez *et al.* 2016; Gianesella *et al.* 2018; Fabbri *et al.* 2020). The site imaged clearly has an effect on the recorded temperature, as does whether the foot imaged is a hind or a front foot (Alsaaod *et al.* 2014).

Studies of IRT and lameness in cattle have established threshold temperatures at which either claw lesions or diseases can be detected. However, the evidence that IRT can be used to detect specific lesions is equivocal with some studies supporting that claim, and others debate at the differences are too small and too variable to be diagnostically useful (Nikkhah *et al.* 2005; Stokes *et al.* 2012; Wood *et al.* 2015). The principal value of IRT thus seems to be as an alternative to LS in detecting cows which could benefit from further examination and, if necessary, treatment (Stokes *et al.* 2012).

Despite the challenges, there is increasing interest in the use of IRT to detect lameness in dairy cows. Alsaaod *et al.* (2015) reported that they found 14 peer-reviewed papers published between 2000 and 2015, which discussed the assessment of thermography to identify and manage lameness in cattle. A database search in June 2021 found that in the six years since the publication of the review by Alsaaod *et al.* (2015), 16 peer-reviewed papers have been published on this topic. This increase may be connected to the decreasing cost of infrared cameras and continued technological advancements resulting in more accessible and inexpensive technology (Montanholi 2015; Gallagher 2018). In addition, this advancement has been prompted by the continued pursuit of quick and non-invasive lameness detection techniques that do not require animal handling. All these factors have increased the focus on IRT as a potential method for identifying lameness.

Some peer-reviewed articles have incorporated data from cows which had access to pasture and housed cows in analyses of IRT and lameness detection (Rodríguez *et al.* 2016; Harris-Bridge *et al.* 2018). However, to date, none have analysed the data from pasture-based cattle separately from housed cattle. For example, Rodríguez *et al.* (2016) assessed the relationship between locomotion score and hoof temperature in dairy cows in Chile. Some of their data came from cows at pasture during spring and early summer (September to January). In the analysis, however, they also included data that came from cows housed for winter (June-August) and did not distinguish between the two groups. Likewise, in their IRT and digital dermatitis study in Scotland, Harris-Bridge *et al.* (2018) included data from 38 cows housed during winter but which had access to pasture during the day in spring and summer (March to August) and cattle that were never on pasture. However, in their analyses, housing status was not included as a variable.

Thus most of the information available on IRT and lameness is related to its use in housed cows, with no studies specifically undertaken in pasture-based production systems. The relationship between IRT and lameness needs investigating in such systems. Additionally, most IRT studies have been undertaken in temperate countries rather than tropical countries like Tanzania. Since foot skin temperature can be influenced by the environment (Main *et al.* 2012; Landgraf *et al.* 2014), activity (Gloster *et al.* 2011), and the type of lameness-causing lesions (Mülling *et al.* 2006; Lawrence *et al.* 2011). Therefore, we need more IRT and lameness data from tropical countries.

2.2.4 In-parlour Scoring

Locomotion scoring requires cows to be observed while walking freely on flat, firm surfaces (Whay 2002). In pasture-based cows, that means that cows can only be locomotion scored while walking back to grazing after milking. An alternative system that scores cows while they are standing to be milked (an in-parlour scoring scheme) would be very useful. However, as far as the author is aware, no such scheme has been developed or tested.

Similar schemes have, however, been developed for use in standing cows. The first such scheme was reported by Leach *et al.* (2009), who developed a stall lameness score (SLS) protocol specifically to detect lameness in tied cows. They included five indicators in their protocol: 1) shifting of weight from one foot to another; 2) rotation of feet from the line parallel to the midline of the body; 3) standing on the edge of a step; 4) resting one foot more than another; 5) uneven weight bearing between feet when moving from side to side, and defined a cow as lame if more than one indicator was present. Their agreement between SLS and locomotion score was only moderate (kappa for the two raters 0.5 and 0.58), and although compared to locomotion scoring, specificity was high for SLS (≥93%), sensitivity was low (≤68%), with the SLS underestimating the proportion of lame cows compared to locomotion scoring. Leach *et al.* (2009) commented that the low agreement between SLS and locomotion score was because mild lameness cases (locomotion score 3 on the 1-5 scale) were likely to be missed by the tie-stall protocol. Excluding rotation of the foot from the protocol and defining lameness as present if one or more indicators were present, improved sensitivity (to ~75%) without markedly decreasing specificity (~90%). Leach *et al.* (2009) was a small study (including only 98 cows) and aimed to prove a concept rather than create a standard test of the SLS importance for lameness detection.

Multiple investigations have employed the SLS (or a modification of the protocol) to evaluate lameness in cows in tie stalls (e.g. (Corazzin *et al.* 2010; Mattiello *et al.* 2011; Radeski *et al.* 2015; Bouffard *et al.* 2017)), of which two were relatively large studies (Gibbons *et al.* 2014; Palacio *et al.* 2017). Gibbons *et al.* (2014), utilising data from 320 dairy cows from nine tie-stall herds, compared SLS employing the indicators described by Leach *et al.* (2009) (excluding foot rotation) and a simplified version of the locomotion scoring system developed by Flower and Weary (2006). Two observers scored cows from video recordings, and Gibbons *et al.* (2014) reported that the intra- and inter-observer agreements for the four SLS indicators were high (ranging from 92 to 100% and 81 to 100%, respectively). Cows were classified as lame using SLS in three different ways: 1) SLS ≥1 (i.e., the presence of at least one indicator); 2) SLS ≥2 (presence of 2 or more indicators), and 3) an SLS of ≥3 (presence of 3 or more indicators). Compared to the locomotion score as a reference standard, SLS of ≥2 was the most accurate definition, with a sensitivity of 63% and specificity of 77%. Gibbons *et al.* (2014) observed that compared to a cow with an SLS of <2, a cow with an SLS of ≥2 had 4.88 times the odds of being lame. In contrast, Leach *et al.* (2009) reported that the SLS overestimated lameness prevalence compared to LS, especially on farms with a low incidence of lameness. However, they concluded that the SLS was a valuable measure of determining lameness prevalence at the herd level.

Palacio *et al.* (2017) compared live SLS to video SLS in 685 cows across 27 herds using the same indicators as Gibbons *et al.* (2014), with an SLS of ≥2 being defined as lame. They reported that live SLS had a sensitivity and a specificity of 83 and 94%, respectively, with video SLS used as the reference standard. Intra- and interobserver agreement ranged from 80 to 100% for detecting a cow as lame when ≥2 indicators were present. Palacio *et al.* (2017) also compared live SLS with live locomotion scoring as per (Gibbons *et al.* 2014) using 250 lactating Holstein cows in five herds. Compared to locomotion scoring as the reference standard, the sensitivity and specificity of live SLS were 59% and 90%, respectively. Based on their dataset, in contrast to that of Gibbons *et al.* (2014) but consistent with Leach *et al.* (2009), Palacio *et al.* (2017) found that using SLS resulted in fewer cows being recorded as lame. Palacio *et al.* (2017) concluded that live SLS could be a practical method for ranking and categorising herds by lameness prevalence, especially when locomotion scoring was not feasible.

Observing cows locked in stanchions is another opportunity for lameness assessment in standing cows. Two studies have assessed whether lameness can be detected in this situation. Hoffman *et al.* (2014) evaluated lameness using data from 1243 cows on four dairy farms in the USA. While watching cows locked in stanchions, they included an arched back, cow-hocked stance (points of the hocks medially directed and claws of the hind hoof laterally directed), widely placed hind limbs, and favouring a leg while standing. The observed individual indicators were compared with locomotion scoring (Sprecher *et al.* 1997), with a cow judged as lame when its locomotion score was ≥3. Hoffman *et al.* (2014) found no association between widely-placed hind limbs and lameness (as detected by locomotion score), but for the other three measures reported sensitivities and specificities, respectively, of 63% and 64% for the back arch, 54% and 57% for cow-hocked stance, and 5% and 98% for favoured limb. Combining a back arch with a cow-hocked stance decreased sensitivity but increased specificity (40 and 81%, respectively). In comparison, either the presence of a back arch or cow-hocked stance to determine lameness increased specificity but reduced sensitivity (78 and 40%, respectively). Hoffman *et al.* (2014) concluded that observation of cows locked in stanchions did not have sufficient sensitivity or specificity to replace locomotion scoring. Nevertheless, they proposed that monitoring for these indicators may be helpful as screening tests for identifying cows that require further examination for lameness detection and treatment.

García-Muñoz *et al.* (2016) studied the relationship between postural and gait abnormalities observed in cows locked in stanchions and lameness as detected using locomotion scoring (Score ≥3; (Sprecher *et al.* 1997)). The indicators used for scoring in the stanchion were the same as those employed by Hoffman *et al.* (2014), i.e., arched back, cow-hocked stance, wide stance, and favoured leg posture. Data from 2009 cows from one dairy farm were used for the study. Consistent with Hoffman *et al.* (2014), they found no association between wide stance and lameness. The other three measures reported sensitivities and specificities, respectively, of 31% and 95% for the back arch, 18% and 91% for cow-hocked stance, and 9% and 98% for the favoured limb. Except for the favoured limb, these specificities were higher, and the sensitivities much lower than those reported by Hoffman *et al.* (2014). The presence of one or more indicators in an individual cow had a sensitivity of 41% and a specificity of 87% for detecting a lameness score ≥3, which was similar to the sensitivity and specificity reported by Hoffman *et al.* (2014). Ultimately, García-Muñoz *et al.* (2016) concluded that the sensitivity for detecting lameness in cows locked in stanchions was too low to be employed as an alternative to locomotion scoring.

Furthermore, García-Muñoz *et al.* (2016) evaluated the observation of cows during milking as a method of detecting lameness. They included four indicators in this analysis, with two observers collecting the data. The first observer was in the milking parlour and recorded the presence of an arched back while the cow entered the milking parlour and cow-hocked stance and favoured limb while it was standing in the milking stall. The second observer evaluated gait, arched back, and favoured limb in the "last group of cows walking towards the parlour." No details were given about how discrepancies between the two sets of observations were dealt with, even for the favoured limb. While one observer recorded this indicator in cows standing to be milked in the parlour, the other recorded it in cows walking to the milking parlour. Specificity and sensitivity were not reported for gait, as although it had the strongest association with lameness (locomotion score ≥3) of any of the indicators (odds ratio 8.8) in the multivariate analysis, it was collinearly dependent on the favoured limb. The other three measures' specificity and sensitivity were very similar to those observed in stanchions. Sensitivity and specificity were 39 and 93% for the back arch, 4 and 98% for the cow-hocked stance, and 7 and 99% for the favoured limb, respectively. The presence of one or more indicators in an individual cow had a sensitivity of 40% and a specificity of 91%. Thus, García-Muñoz *et al.* (2016) concluded that the sensitivity of lameness detection during milking was too low for it to be utilised as an alternative to classic locomotion scoring.

All these findings indicate that non-locomotory lameness examinations may be appropriate for recognising cows that require close inspection for lameness or for estimating lameness prevalence on a farm. However, none of these studies has been conducted on cattle kept at pasture permanently and milked using a rotary parlour. The latter is important because rotary parlours are mainly employed in larger dairy farms where the number of cows per full-time staff member is higher (DairyNZ 2015), thus raising the significance of the benefit of alternatives to visual locomotion scoring. However, not all indicators suggested by Leach *et al.* (2009) can be evaluated effectively in cows milked in rotary parlours. For example, it is impossible to assess uneven weight-bearing while moving the cow from side to side or standing on the edge of a stall. Thus for lameness scoring, while cows are being milked in a rotary parlour, we require indicators that can be evaluated by observation only to perform in-parlour scoring. Potential indicators include arched back (Hoffman *et al.* 2014; García-Muñoz *et al.* 2016), overgrown hooves (Toussaint Raven 1985; Shearer and van Amstel 2001; Van der Tol *et al.* 2004), observed claw injuries (Haskell *et al.* 2006; Shearer and Van Amstel 2007), swelling of the hock or heel (Burow *et al.* 2013; Kester *et al.* 2014) and swelling around the coronary band (Cramer *et al.* 2008). All these indicators could be utilised alongside shifting weight and abnormal weight distribution to evaluate the risk of lameness in the milking parlour.

2.2 Lameness Management, Prevention, and Control in Dairy Cattle

2.3.1 Introduction

Lameness is well known for causing economic loss and welfare problems in dairy cattle (Laven and Holmes 2008; Huxley 2013; Whay and Shearer 2017). It is a complex condition with a significant challenge influenced by a large range of risk factors. Control and management of infectious lameness require a targeted therapeutic approach alongside management changes, especially for bovine digital dermatitis and bovine foot rot are based on the development of appropriate biosecurity programs (Laven and Hunt 2002; Evans *et al.* 2016; Solano *et al.* 2017).

In contrast, such clear solutions are not available for non-infectious causes of lameness, which remain the main challenge concerning lameness in dairy cattle (Murray *et al.* 1996; Potterton *et al.* 2012; Shearer *et al.* 2015). As discussed earlier, it is pressure load on the corium which leads to CHDL, the principal non-infectious cause of lameness, and much of lameness prevention is focused on reducing the mechanical pressure and stress within the foot (Van der Tol *et al.* 2004). This focus has led to the development of prophylactic hoof trimming, which aims to produce optimal claw conformation and minimise abnormal weight-bearing within the foot (Toussaint Raven 1985; Shearer and van Amstel 2001).

2.3.2 Importance of Claw Trimming

Claw trimming is currently the most widely used management strategy for addressing claw lesions causing lameness in dairy cows (Shearer and van Amstel 2001; Stoddard and Cramer 2017); there are two main types of hoof trimming:

1) Prophylactic (functional) trimming. This trimming aims to optimise the balance in weight-bearing between the claws by removing excess horn growth (Toussaint Raven 1985; Shearer and van Amstel 2001). Effective hoof trimming balances the load between the claws (Van der Tol *et al.* 2004) and improves the gait (Aoki *et al.* 2006), and reduces the risk of lameness associated with CHDL, i.e. white line disease, sole haemorrhage, and sole ulcers (Van der Tol *et al.* 2004). Several studies have shown that prophylactic claw trimming reduces the risk of lameness, supports animal welfare, and improves performance in dairy farms worldwide (Manske *et al.* 2002; Aoki *et al.* 2006; Hernandez *et al.* 2007; Groenevelt *et al.* 2014; Sadiq *et al.* 2021b). For instance, Manske *et al.* (2002) evaluated the impact of hoof trimming on hoof health in dairy cows on 77 dairy farms in Sweden (3444 cows) over a two-year period. They found that increasing the frequency of prophylactic trimming decreased hoof lesions and lameness prevalence. Similarly, Hernandez *et al.* (2007), using data from 333 dairy cows in the USA, found that prophylactic hoof trimming during mid-lactation decreased lameness incidence during late lactation (≥205 days in milk) by 25%.

   One advantage of routine herd hoof trimming that is often underestimated is that as part of the process, cows with early lesions can be identified, and their progression to more severe lesions halted (Fjeldaas *et al.* 2006; Hernandez *et al.* 2007; Groenevelt *et al.* 2014; Sadiq *et al.* 2021b). Thus, a well thought out regime for routine foot trimming is a useful tool for monitoring claw health and reducing claw lesions in housed cows (Fjeldaas *et al.* 2006; Hernandez *et al.* 2007; Sadiq *et al.* 2021b). However, the evidence for the benefit of prophylactic hoof trimming is more limited in cattle at pasture than in housed cows, with only one published study (Bryan *et al.* 2012) of prophylactic hoof trimming on pasture-based dairy cattle.

2) Therapeutic (corrective) trimming. This trimming involves removing debris and devitalised tissue from CHDL and other non-infectious lesions (Fjeldaas et al. 2006; Bryan et al. 2012; Horseman et al. 2013). Therapeutic trimming, when done properly, like prophylactic trimming, should aim to balance the hoof weight bearing and restore normal hoof conformation (Toussaint Raven 1985). The trimming should also reduce the pressure at the site of damage; this can be aided by the application of orthopaedic hoof blocks (Thomas et al. 2016; Shearer and van Amstel 2017).

Effective claw trimming, whether prophylactic or therapeutic treatment-focused, requires efficient tools and animal/user-friendly handling facilities (Shearer and van Amstel 2001). These can range from simple equipment (hoof testers, nippers, rasps and hoof knives) to power tools (grinder and disc attachments). Similarly, cow restraint can also be scaled to match the system (from leg ropes to purpose-made lameness crushes or tilt tables) (Shearer and van Amstel 2001; Pesenhofer *et al.* 2006; Hernandez *et al.* 2007). In countries practising routine hoof trimming, there are hoof care training and service centres and trained personnel (hoof trimmers) working under the umbrella of professional organisations to undertake this work. For example, Dutch hoof care (www.dutchhoofcare.com/) in the Netherlands, Cow Care specialists in hoof trimming in Europe (cowcare.eu/training-and-consultation/), and VeeHof hoof care specialists (www.veehof.co.nz/trimming/services/) in New Zealand. These professional organisations are key stakeholders in preventing lameness in dairy herds.

2.3.3 Claw Trimming Methods and their Applications

Prophylactic hoof trimming aims to provide nearly equal weight-bearing between claws and maintain their function under various management systems. Many claw trimming techniques have been described and published in multiple sources, including peer-reviewed journals (Shearer and van Amstel 2001; Manske *et al.* 2002; Ouweltjes *et al.* 2009; Tanida *et al.* 2011; Van Hertem *et al.* 2014; Stoddard 2018; Sadiq *et al.* 2021a), conference proceedings (Daniel 2014; Siebert 2017), and textbooks (Toussaint Raven 1985; Blowey 2020). A recent review by Sadiq *et al.* (2020) reported four main claw trimming procedures, including the Dutch five-step ((Toussaint Raven 1985)), White Line (Blowey 2020), White Line Atlas (Daniel 2014), and the Kansas hoof trimming method (Siebert 2017). Classification of these claw trimming procedures depends on how the technique influences the sole angle compared to the metatarsal or metacarpal bones as a reference. The five-step Dutch method promotes a flat claw sole surface (Toussaint Raven 1985; Shearer and van Amstel 2001; Manske *et al.* 2002). Using this method, lateral (abaxial) and medial (axial) hoof walls are made level and perpendicular to the metatarsal or metacarpal bones.

The primary goal of the Dutch method pioneered by Toussaint Raven (the father of hoof trimming) is balancing weight-bearing between the claws, with trimming performed to restore the shape and proper functioning of the claws (Toussaint Raven 1985; Shearer and van Amstel 2001). The Dutch method involves five main steps: 1) trimming the toe length of the medial claw to 75 mm; 2) making the lateral claw equal in length to the medial (or as near as possible); 3) making the sole flat and paring off the toe to 5 mm sole thickness; 4) relieving the weight on the affected claw (if lesions present), and 5) removing loose horn and hard ridges. For the front feet, the same procedure is followed, except that the first step starts with the lateral claw instead of the medial claw.

The White Line procedure proposed by Blowey (2020) is similar in principle to the Dutch five-step method. The main difference in this trimming procedure is careful observation of the sole thickness during claw trimming (sole reading) - the claw is trimmed until the white line becomes noticeable at the toe area. Estimating sole thickness in both the Dutch and White Line techniques is critical to balancing weight-bearing between the hindlimb claws and avoiding over trimming (Nuss and Paulus 2006; Meyer *et al.* 2007; Archer *et al.* 2015). To avoid over-trimming, Nuss and Paulus (2006) suggested that 7–8 mm of sole horn thickness should be preserved in the medial claw to allow for a lateral sole thickness of at least 5 mm when levelling both hind claws. Slight anatomical differences between the medial and lateral claw are responsible for the sole horn thickness differences. Nuss and Paulus (2006) used cadaver feet from German Simmental cows to show that the sole of the lateral claw protruded approximately 2–3 mm above the sole of the medial claw after standardisation of sole thickness. In addition, measurements of the metatarsal bones in calves showed that the lateral condyle is longer than the medial condyle (Nacambo *et al.* 2007). Therefore, these anatomical differences should be accounted for when applying a particular claw trimming procedure.

Vic Daniel described the White Line Atlas hoof trimming procedure (Daniel 2014). The primary principle of this hoof trimming procedure is to strengthen the white line by keeping the three layers of the wall horn, white line, and solar horn level (see Figure 2.1). Thus, the White Line Atlas trimming technique advocates that a suitable biomechanical shape on individual claws is attained at the end of the trimming process. The procedure does not focus on claw length and toe angle but on hoof size and shape. This procedure considers six biomarkers to undertake hoof trimming correctly, including white line, heel fulcrum, pressure ridge, break-over point, sole horn thickness, and hairline. However, this technique has not yet been explored in a peer-reviewed publication.

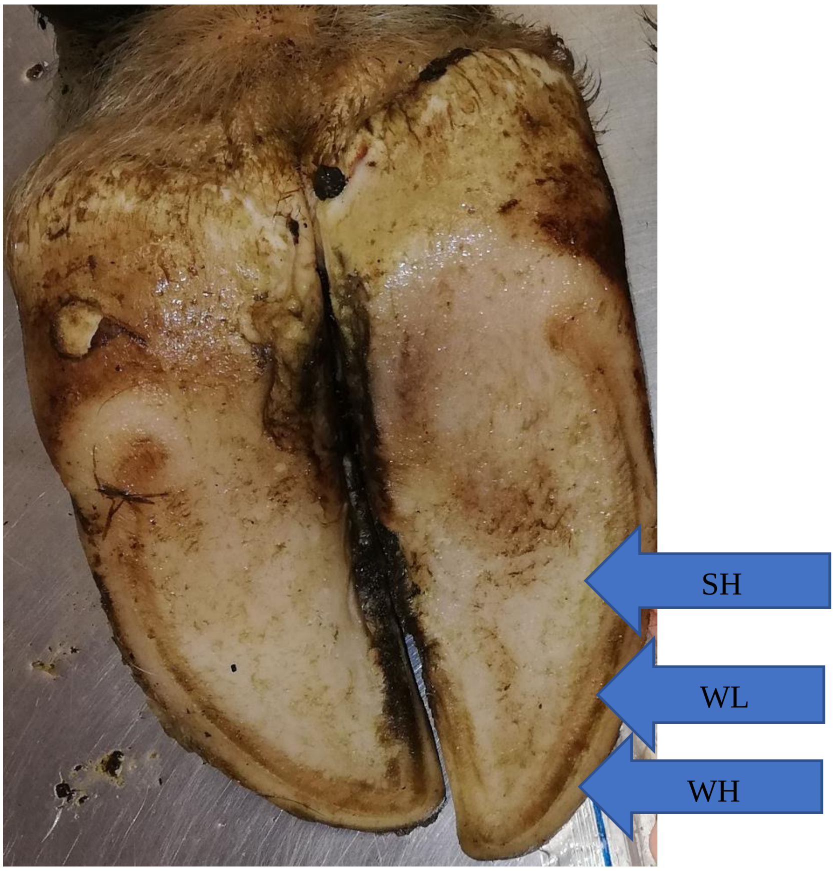

Figure 2. 1: Illustration of the key areas of the claw sole that the White Line Atlas hoof trimming procedure focuses on during trimming. SH = sole horn, WL = white line, and WH = wall horn.

The Kansas hoof trimming method was designed based on the deviations in claw structure between individuals (Siebert 2017). As a result, this trimming procedure aims to overcome the issue of normal variation by accurately trimming the toe to its individual normal for sole thickness. This trimming method promotes an objective approach for defining standard sole thickness during the hoof trimming procedure. The procedure utilises four attributes: wall length, heel depth, sole thickness, and sole gradient to describe a standard claw structure. The Kansas method also is based predominantly on anatomical landmarks that occur within the overgrown sole horn, such as a white powdery (dehydrated) substance called pith. These features are employed to describe sole thickness and typical toe conformation accurately. Since sole horn containing pith only occurs outside the normal sole thickness as part of the natural shedding process (Siebert 2017), trimming the sole until pith inclusions disappearance is said to be an accurate measure of when the sole has been pared back to its optimal thickness. Because pith or shedding sole horn occurs across the whole sole surface, from toe to heel and from axial to abaxial, trimming the whole distal surface of the claw to the plane where all pith has been removed results in an individually customised dorsal wall length and heel height.

The Kansas method describes three objective hoof trimming procedures: visual identification, ventral surface, and pith interpretation. The choice of a specific procedure relies on the status of sole shedding. First, the visual identification procedure is employed to objectively trim the sole to its normal sole surface when shedding is normal (no blockage of shedding) and there is no pith in the overgrown sole horn. Next, the ventral surface procedure is also utilised when there is no pith in the overgrown environmentally hydrated sole horn. However, this procedure can also be employed for trimming the overgrown sole horn to accurately locate the normal sole surface when shedding is totally or partially impeded.

Last, the pith interpretation procedure (reading the pith) is utilised to accurately measure the normal sole surface when shedding is wholly or partially blocked, and the pith is present in the overgrown environmentally hydrated sole horn. This procedure involves objectively measuring the zone of the normal sole surface by trimming the ventral surface until there is the total disappearance of the pith. Like the white line atlas procedure, this technique has not been tested in a peer-reviewed publication.

Of the four methods outlined above, the Dutch method is the one that has been most extensively tested. As a result, numerous modifications to the Dutch method have been described; for instance, the concave method involves paring off the sole horn to a thickness of 3 to 5 mm under the pedal bone, resulting in a more concave shape at the sole-ulcer site (Ouweltjes *et al.* 2009). However, that study found no significant difference between the standard Dutch and concave methods on locomotion scores and claw lesions or diseases in housed cows. Another modification is that described by Stoddard (2018). In addition to standard Dutch hoof trimming, this technique involves the removal of more sole horns under the flexor tuberosity of the pedal bone (sole-ulcer site) (see Figure 2.2). As a result, it decreases the weight-bearing contact surface of the lateral claws (thus decreasing pressure load). Stoddard (2018) found that this technique decreased the risk of lameness by 10.5% in the subsequent lactation in cows trimmed in the middle of their first lactation. However, the method did not affect lesion prevalence in multiparous cows.

Figure 2. 2: Illustration of standard functional hoof trimming using the Dutch five-step method on a cow's overgrown right hind foot kept at pasture permanently.

A: No sole horn pared off on either claw at a typical sole ulcer site. **B:** Sole horn pared off on both claws at a typical sole ulcer site approximately 40 to 42 mm from the abaxial hoof wall. An arrow shows a typical ulcer site on the lateral claw, where several studies have primarily focused on modelling for adaptational functional hoof trimming methods (Ouweltjes *et al.* 2009; Stoddard 2018; Sadiq *et al.* 2021a)**.**

Sadiq *et al.* (2021a) used a modified Dutch method whereby the weight-bearing claws (lateral - hind limbs and medial – forelimbs) were pared up to 20 mm away from the abaxial wall (see Figure 2.2), and the counterpart claws were trimmed according to the Dutch method.

This study found no significant difference (34.6 versus 28.1%) between the two hoof trimming procedures in subsequent claw lesion prevalence.

The Dutch method has been used in large numbers of dairy cattle worldwide over the last decades (Manning *et al.* 2016), being employed in multiple breeds (Manske *et al.* 2002; Somers *et al.* 2003; Fjeldaas *et al.* 2006), age groups (Ouweltjes *et al.* 2009; Maxwell *et al.* 2015), and production systems, e.g. housed (Somers *et al.* 2003; Fjeldaas *et al.* 2006; Ouweltjes *et al.* 2009), and pasture-based cows (Bryan *et al.* 2012). The wide range of use makes it the most popular hoof trimming method in dairy cattle.

2.3.4 Problems with Claw Trimming

The main problem associated with claw trimming is over trimming, which produces thin soles, particularly at the toe and lateral wall (Nuss and Paulus 2006; Archer *et al.* 2015). Over trimming can predispose the corium to trauma both from within by the distal phalanx and the harsh external environments, e.g. concrete or stony surfaces, subsequent sole haemorrhages and ulcers (van Amstel *et al.* 2003; Mahendran and Bell 2015; Manning *et al.* 2016). Moderate over trimming may be more common than assumed. Nuss and Paulus (2006) found that firm compliance with the principles of functional claw trimming proposed by (Toussaint Raven 1985) in German Simmental cows left them with inadequate protection of internal claw structures. The thickness of the sole horn is critical as far as lameness is concerned (Bicalho et al. 2009; Stambuk et al. 2019; Wilson et al. 2021). Thus, attention to technique, landmarks, and potential pitfalls is important to ensure that adequate sole thickness is maintained during hoof trimming.

Several studies have demonstrated that in the modern dairy cow, a claw length longer than the 75 mm recommended by Toussaint Raven might be better. For example, Reilly *et al.* (2017), using the five-step Dutch method at 11 dairy farms with Holstein, Holstein-Friesian, and Friesian breeds in Southwest England, reported that 18.4% of cows needed a dorsal wall length of >75 mm to ensure adequate sole thickness (estimated by ultrasound), they suggested that 85 mm may be more appropriate for functional/prophylactic hoof trimming. Archer *et al.* (2015) recommended in adult Holstein Friesian dairy cows a toe length of 90 mm. They suggested that this length could be reduced to 85 mm in primiparous and second calvers. All these findings show a need for further research on the impact of routine trimming procedures under different production conditions to address the challenges arising from the existing methods.

2.3.5 Timing and Frequency of Claw Trimming

Claw trimming, to be effective, needs to prevent lameness, as once lameness has occurred, a cow is far likelier to become lame in subsequent lactations than cows which have never been lame (Reader *et al.* 2011; Huxley 2013). Thus deciding on the strategy for prophylactic trimming is crucial. Too often and the risk of over trimming increases; not often enough and the risk that cows will become lame increases. Claw trimming practices range from no prophylactic trimming (Fjeldaas et al. 2006; Espejo and Endres 2007) through trimming every cow once a year (usually at dry-off or mid-lactation) (Manson and Leaver 1988a; Ouweltjes *et al.* 2009; Machado *et al.* 2010), in early lactation (Maxwell *et al.* 2015), to trimming multiple times per year (Manske *et al.* 2002; Somers *et al.* 2003; Van Hertem *et al*. 2014). However, despite all of this published research, there are still questions about the optimal prophylactic trimming strategy. For example, a recent study on dairy farms in Great Britain by Pedersen *et al*. (2022) found that most farmers undertake preventive hoof trimming at dry off (72.2%). However, they question when they should perform prophylactic hoof trimming and which is the best trimming technique. There are still many unanswered questions regarding the timing, technique, and utility of routine claw trimming as a lameness management strategy in different systems, leaving this an area where further research is needed.

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Chapter Three: Evaluating Alternatives to Locomotion Scoring for Lameness Detection in Pasture-Based Dairy Cows in New Zealand: Infra-Red Thermography

Foreword: This chapter covers the study that evaluated infrared thermography against locomotion scoring for lameness detection in dairy cows in pasture-based production systems in New Zealand. Data were collected from a 940-cow dairy farm in New Zealand with cows observed at two consecutive afternoon milkings. Locomotion scoring was undertaken at the first milking, and thermal imaging of the hind feet at the second milking. Mean foot skin temperature measured from the plantar aspect of hind limbs at a cut-off point of 34.5 °C produced a sensitivity of 80.0% and a specificity of 92.4% for identifying cows with increased locomotion score (locomotion ≥2 (lame)). The study has been published and can be accessed via this link: https://doi.org/10.3390/ ani12060703. In this thesis, the article has been presented as it appears in journal format and style.

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Article

Evaluating Alternatives to Locomotion Scoring for Lameness Detection in Pasture-Based Dairy Cows in New Zealand: Infra-Red Thermography

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Simple Summary: Early detection accompanied by effective treatment is vital to minimise the negative impacts of lameness in dairy cows. Locomotion scoring is commonly used for detecting lameness but can be challenging to implement effectively in cows at pasture-based systems. One potential alternative detection is measuring foot skin temperature using an infrared camera. Data were collected from a 940-cow dairy farm in New Zealand with cows observed at two consecutive afternoon milkings. Locomotion scoring was undertaken at the first milking and thermal imaging of the hind feet at the second milking. As the locomotion score increased, mean foot skin temperature increased, showing that measuring temperature could be a useful alternative to locomotion scoring. However, the process needs to be speeded up and automated if it is to be used widely.

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Abstract: Lameness in cattle is a complex condition with huge impacts on welfare, and its detection is challenging for the dairy industry. The present study aimed to evaluate the association between foot skin temperature (FST) measured using infrared thermography (IRT) and locomotion scoring (LS) in dairy cattle kept at pasture. Data were collected from a 940-cow dairy farm in New Zealand. Cows were observed at two consecutive afternoon milkings where LS was undertaken at the first milking (4-point scale (0–3), DairyNZ). The next day, cows were thermally imaged from the plantar aspect of the hind feet using a handheld T650sc forward-looking infrared camera (IRT). The association between FST and locomotion score was analysed using a generalised linear model with an identity link function and robust estimators. ROC curves were performed to determine optimal threshold temperature cut-off values by maximising sensitivity and specificity for detecting locomotion score ≥ 2. There was a linear association between individual locomotion scores and FST. For mean temperature (MT), each one-unit locomotion score increase was associated with a 0.944 °C rise in MT. Using MT at a cut-off point of 34.5 °C produced a sensitivity of 80.0% and a specificity of 92.4% for identifying cows with a locomotion score ≥ 2 (lame). Thus, IRT has a substantial potential to be used on-farm for lameness detection. However, automation of the process will likely be necessary for IRT to be used without interfering with farm operations.

Keywords: lameness; infrared thermography; locomotion scoring; dairy cows; pasture-based

1. Introduction

Lameness is a complex multifactorial condition characterised by an abnormal gait, pain, and discomfort. Research shows that, in addition to its major impact on dairy cow welfare [1–3], lameness is also responsible for substantial economic losses due to treatment costs [4], reduced milk production [5–7] and reproductive performance [8–10], and increased culling [10–14]. Therefore, early detection and treatment of lame cows are vital to minimise the pain and discomfort associated with lameness [15,16] and to reduce the risk of irreversible claw damage [17]. Thus, early intervention improves welfare and decreases the economic impact of lameness but requires active lameness detection.

Locomotion scoring (LS) is the most used method for detecting lameness on dairy farms. An observer rates the cow with a discrete score based on assessing various features of gait and posture. Numerous LS systems have been developed for use on-farm; Schlageter-Tello et al. [18] identified 25 different LS systems that had been published in the peer-reviewed literature by 2014. These systems vary in the features they use. For example, while Manson and Leaver [19] included the ability of a cow to turn, Sprecher et al. [10] did not, with the opposite being true for arching of the back. LS systems also vary in the scale they use, ranging from a simple two-point system (sound or lame) [20] to as many as nine points [19,21]. The most commonly cited system is the 5-point (1 to 5) system proposed by Sprecher et al. [10] as reported by Schlageter-Tello et al. [18]. While this system has been used in New Zealand [22], the current industry standard scheme is a 4-point (0 to 3) system based on a similar system used in the UK [23].

The large number of different LS systems identified by Schlageter-Tello et al. [18] shows no consensus on the optimal system, with each system having its own advantages and disadvantages. One crucial problem is the subjective nature of LS, with both within- and between-observer variation being high, especially when training is limited [18,24–26]. Visual LS is also time-consuming and can require significant labour resources, especially in larger herds where the rate at which cows exit the milking parlour can add significant difficulties for LS. This issue led Ranjbar et al. [27], who investigated risk factors for lameness in Australian dairy herds, to record locomotion scores as a tally rather than at the individual cow level. Furthermore, in pasture-based systems where LS is usually undertaken outside as cows return to pasture after milking, environmental factors such as sunlight, wind, and rain can make LS more difficult for the observer and, therefore, less accurate.

One potential alternative to visual LS is infrared thermography (IRT), a non-invasive technique that measures body surface temperature and produces a pictographic representation of the imaged structure [28]. The infrared camera absorbs infrared radiation and generates an image derived from the amount of heat produced. Each pixel in the produced image represents the recorded surface temperature of the anatomical region [29]. The images can be presented both in greyscale and colour. When presented in the greyscale or colour, white or red are the hottest region, whereas black or blue represent the coldest region [28,30].

Extremities' and surface skin temperature mostly depends on blood perfusion and tissue metabolism rate [31]. Changes in blood flow can impact the amount of radiated heat and therefore be detected by IRT [28]. One of the key reasons for changes in tissue blood flow is the inflammatory process. This link between inflammation and tissue temperature has stimulated the use of IRT as a diagnostic tool for lameness. However, inflammation is not the only process affecting foot temperature. Other factors, such as individual animal variation, physiological state, environment, and even activity level, can influence foot temperature [32–34]. For example, foot temperatures measured at the coronary band are higher in early to mid-lactation ($\leq$200 days in milk) compared to late lactation (>200 days in milk) [32,34,35]. All these factors need to be considered when evaluating the utility of IRT as a method of lameness detection in dairy cattle.

Nevertheless, there is a definite potential for IRT to be used for both screening for lameness and monitoring after treatment. For example, Wood et al. [36] recorded foot temperature fortnightly at milking using a non-contact infra-red thermometer alongside LS. They found that foot temperature was highest when a cow was identified as lame. Treatment resulted in a marked reduction in foot temperature, with the lowest foot temperature recorded six weeks after treatment. They noted that this temperature was lower than the temperature recorded six weeks before treatment, suggesting that an inflammatory process had been present in the foot for at least six weeks before detecting lameness using LS.

There is increasing interest in the use of IRT to detect lameness in dairy cows. This increase may be related to the reducing costs of IRT and continued technical advances, which has meant that IRT has become affordable [37,38]. However, almost all the published studies of lameness and IRT have been undertaken in housed cows rather than in cows kept permanently at pasture, the production system that predominates in New Zealand. Furthermore, as the environment influences foot temperature [39,40], animal activity [33], and the type of lesion that is likely to be causing lameness [41,42], the relationship between IRT and lameness may be different in pasture-based systems.

Of the peer-reviewed studies looking at IRT and lameness detection, all the papers that include data from cattle at pasture also include data from housed cows. As far as the authors know, no peer-reviewed study has analysed pasture-based dairy cows data separately from housed dairy cows data. For example, some of the data evaluated by Rodríguez et al. [43] came from cows at pasture during spring and early summer (September to January). However, they also included data from cows housed for winter (June-August) and did not differentiate between the two groups. Similarly, Harris-Bridge et al. [44] included data from cattle that were allowed to graze during the day in spring and summer (March to August) as well as from cattle that were housed during the winter or which were permanently housed but did not include housing status as a variable in their analyses.

Further data on the association between IRT and lameness are needed in cattle at pasture. This is particularly relevant for New Zealand, as cattle are kept at pasture and never housed on the great majority of farms. So, we hypothesised that measuring the foot skin temperature from the plantar aspect of the hind feet of dairy cows would predict higher locomotion scores (lameness). Therefore, this study aimed to evaluate the association between hindfoot skin temperature, measured using IRT and LS in New Zealand dairy cattle kept permanently at pasture.

2. Materials and Methods

2.1. Animals and Farm Location

The study was undertaken in February on a 940-cow dairy farm in the Tararua district of the North Island of New Zealand. The farmer was a client of the Massey Farm Practice and when informed about this project was interested in participating. The herd was a split calving herd with 480 cows calving in the Spring (July–October) and 460 cows in the Autumn (March–May). Most of the cows were Friesian, with approximately 20% Jersey and 5% Friesian cross Jersey. The cows were of mixed ages ranging from 2 to 10 years with four years on average.

The cows were milked twice daily through a 60-unit rotary milking parlour. The milking herd was managed as two roughly equal groups, grazing separate paddock rotations and milking in succession. Lame cows were generally identified by farm staff and then presented for treatment by a veterinarian. Cows identified as lame by farm staff were kept in a separate “lame group” in paddocks near the milking parlour until their lameness had improved enough to return to their main herd section. The lame group was excluded from the present study as, to minimise walking and standing time, cows in the group were milked only in the morning session. Based on farm treatment records of 50 lameness cases over the lactation, the main causes of lameness were white line disease (54%), sole injury (16%) and foot rot (8%). No digital dermatitis was identified at any time.

Data collection involved observation of cows at two consecutive afternoon milkings. Locomotion scoring was undertaken at the first milking, with IRT being used at the second.

2.2. Locomotion Scoring

Individuals were identified by their ear tag number and locomotion scored as they exited the milking parlour by CWW using the DairyNZ lameness score [45]. This scoring system has been adapted from the Agriculture and Horticulture Development Board (AHDB) mobility score to create a system that can be used to score cattle when they are walking back to pasture after being milked [23]. The DairyNZ lameness score is based on assessing walking speed, walking rhythm, weight-bearing, back alignment, head position, stride length, and foot placement (Table 1).

Table 1. The gait and posture attribute used during locomotion scoring with the DairyNZ system [45].

Score	Clinical Term	Evaluation Criteria
0	Sound	The cow walks confidently, even weight-bearing and tracks up.
1	Imperfect locomotion	The cow walks unevenly, does not track up, with a mildly arched back when walking.
2	Lame	An arched back, the favoured limb moves faster than the lame leg, feet placed unevenly, head bobs up and down when walking.
3	Severely lame	Walks very slow, reluctant to bear weight, arched back, and head bobs obvious.

Prior to the study commencing in February 2018, CWW was trained in locomotion scoring. The training consisted of observing training videos created by DairyNZ [46] and AHDB [47], followed by supervised locomotion scoring on-farm (live cows) with a trained and experienced observer until the trainer was satisfied that the trainee could perform locomotion scoring effectively.

Visit 1: The whole herd was locomotion scored as they exited the milking parlour after afternoon milking. Locomotion scores were recorded at the individual cow level; the score was not recorded if a cow could not be identified from its ear tag. The locomotion scoring evaluation area was a flat concrete surface about 20 m in length. This walking distance was enough to assess cows' gait and posture attributes while exiting the milking parlour.

2.3. Infrared Thermography

Visit 2: Infrared thermography (IRT) imaging was performed during the next afternoon milking using a handheld T650sc Forward-looking Infrared camera (FLIR Systems, Wilsonville, OR, USA). On this day, the recorded atmospheric temperature was 22 °C. The infrared camera employed in this study had the emissivity value set at 0.95 (this relates to the capability of the object or body to absorb and emit infrared radiation).

During this visit, the speed of the rotary platform was reduced to allow routine herd pregnancy diagnosis to be undertaken. CWW performed infrared thermography imaging of the claws in the hind feet at the three-quarter point on the rotation towards the exit before cows were pregnancy tested by another veterinarian. With the observer stationary (at a distance of approximately 1 metre from the cow) and the platform rotating, a plantar image of both hind feet was obtained of every fourth cow and her identity recorded. No claw preparation was performed, feet were not washed before imaging.

The foot images were later analysed using FLIR Tools software (FLIR Systems, Wilsonville, OR, USA). The surface temperature estimates were obtained from seven zones on each hind limb (Figure 1).

The maximum temperature for each zone was used for analysis in line with previous infrared studies aimed at lameness detection in the cow [48,49].

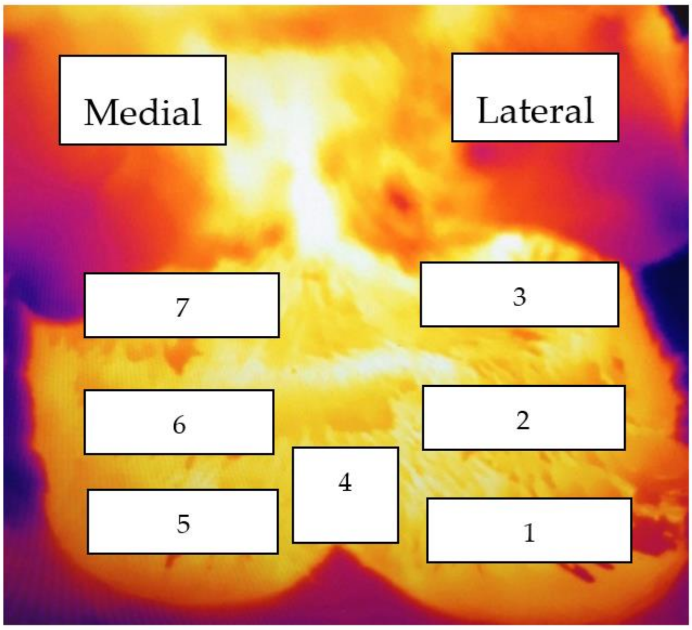

Figure 1. Infrared thermography image of the plantar aspect of the right hind foot overlaid to illustrate the seven zones for which estimates of surface temperature were obtained. On the lateral claw; zone 1: coronary band (CB), zone 2: above the coronary band (ACB), zone 3: below accessory digit (BAD), zone 4: interdigital space (IDS), zones 5 to 7 are the equivalent to zones 1 to 3 but on the medial claw.

2.4. Statistical Data Analyses

All data were analysed using SPSS version 25 (IBM Corporation, Armonk, NY, USA) except where stated. Descriptive statistics exploration was undertaken for each zone temperature measure. First, the normality of foot temperature was visually assessed using Q-Q plots and histograms. A generalised linear marginal repeated measures model was then used to evaluate the effect of the foot and zone within the foot on skin temperature. Foot (right or left hind) was the dependent variable, zone within foot the repeated variable and skin temperature the outcome variable. Covariance structure was identified using the Akaike information criterion. Residuals were checked for normality using Q-Q plots and histograms. Posthoc pairwise comparisons between marginal means were then used to compare between zones (with the Šidák correction for multiple comparisons [50]).

The association between locomotion score and foot temperature was tested using six temperature measures (summarised in Table 2). The relationship between these temperatures and locomotion scores was explored using box plots. This identified significant heteroscedasticity when foot temperature was compared across locomotion scores. Therefore, the association between foot skin temperature and locomotion score was analysed using a generalised linear model with an identity link function and robust estimators [51]. Each temperature definition was analysed as the outcome variable with LS as the predictor variable.

Table 2. Definitions of the infrared thermography estimates utilised for analysis.

Foot/Zone *	Description
Mean temperature	Average temperature, across both feet (all 14 zones)
Hottest zone	Highest zone temperature, across both feet (all 14 zones)
Hottest zone 4	The highest zone 4 temperature on either foot
Hottest coronary band (CB)	The highest zone 1 or 5 temperature on either foot
Hottest above the coronary band zone (ACB)	The highest zone 2 or 6 temperature on either foot
Hottest zone below the accessory digit (BAD)	The highest zone 3 or 7 temperature on either foot

* For all analyses, the maximum temperature for each zone was used for the analysis.

A receiver operator characteristic (ROC) curve analysis was then performed. Six curves were created, one for each definition with categorised locomotion score (Lame (locomotion score $\geq$ 2) vs. not lame (locomotion score < 2)) to establish the sensitivity and specificity of IRT to predict locomotion score $\geq$ 2. The area under the curve (AUC) and coordinates of the curve (CC) were used to assess a model's predictive accuracy. In addition, optimal threshold temperature cut-off values were determined by maximising sensitivity plus specificity. The statistical package software MedCalc Version 19.5.1 (MedCalc Software, Ostend, Belgium) was then used to calculate positive and negative predictive values for those optimal cut-offs.

3. Results

Data for both locomotion scoring and infrared thermography (430 thermograms, one per hind limb) were available from 215 cows from the 940-cow herd.

3.1. Effect of Foot and Foot Zone on Skin Temperature

There was no evidence of a meaningful difference between feet in skin temperature; left and right foot mean temperatures were 33.37 °C (95% CI: 33.286–33.443) and 33.58 °C (95% CI: 33.512–33.657), respectively, with a mean difference of 0.21 °C (95% CI: 0.18–0.45). However, differences between zones were identified; the difference between the zone with the lowest mean temperature (zone 6) and the zone with the highest mean temperature (zone 4) was 1.11 °C (95% CI: 0.87–1.34).

Although mean temperatures were higher for the zones on the lateral claw than the equivalent zones on the medial claw (see Table 3, Figure 2), these differences were small (between 0.02 and 0.1 °C).

Table 3. The mean temperature and 95% confidence interval for zones 1–7 (see Figure 2) for both hindlimbs (430 feet) of 215 cows (degrees centigrade).

Zone	Mean	95% Confidence Interval	
		Lower Bound	Upper Bound
1	33.51	33.375	33.646
2	33.03	32.889	33.165
3	33.65	33.507	33.787
4	34.12	33.986	34.250
5	33.46	33.323	33.596
6	33.01	32.869	33.148
7	33.55	33.414	33.691

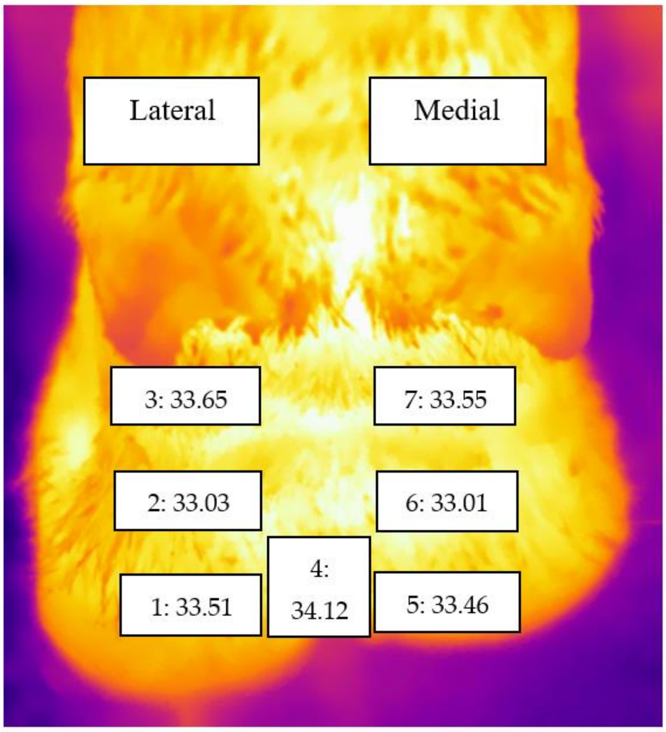

Figure 2. Thermogram (plantar aspect of left hind foot) illustrating the mean temperature (degrees centigrade) for zones 1–7 in the left hindfoot. On the lateral claw; zone 1: coronary band, zone 2: above the coronary band, zone 3: below the accessory digit, zone 4: interdigital space, zones 5 to 7 are the equivalent to zones 1 to 3 but on the medial claw.

3.1.1. Infrared Thermography versus Locomotion Scoring

Of the 215 cows with data from both infrared thermography and locomotion scoring, 86 had score 0 (40%), 99 had score 1 (46%), 27 had score 2 (12.6%), and 3 had score 3 (1.4%). Due to the low number of cows with a score of 3, the data from the cows with scores 2 and 3 were amalgamated as a score of ≥2.

For all six temperature measures (Table 2), the temperature was higher for cows with a locomotion score of 1 than those with a score of 0 and higher for cows with a locomotion score of ≥2 than those with a score of 1.

Since the results for all zones showed the same trend, data are presented for mean temperature (MT) and the hottest coronary band zone (CB) only. The remaining data are presented in Appendix A. For MT, the mean difference between cows with scores 0 and 1 was 1.24 °C (95% CI: 0.9–1.58), and between scores 1 and ≥2 cows, it was 1.06 °C (95% CI: 0.58–1.54). The equivalent figures for CB were 1.2 °C (95% CI: 0.84–1.56) and 0.98 °C (95% CI: 0.47–1.49). The boxplots for MT and CB temperature measures are presented in Figures 3 and 4, respectively.

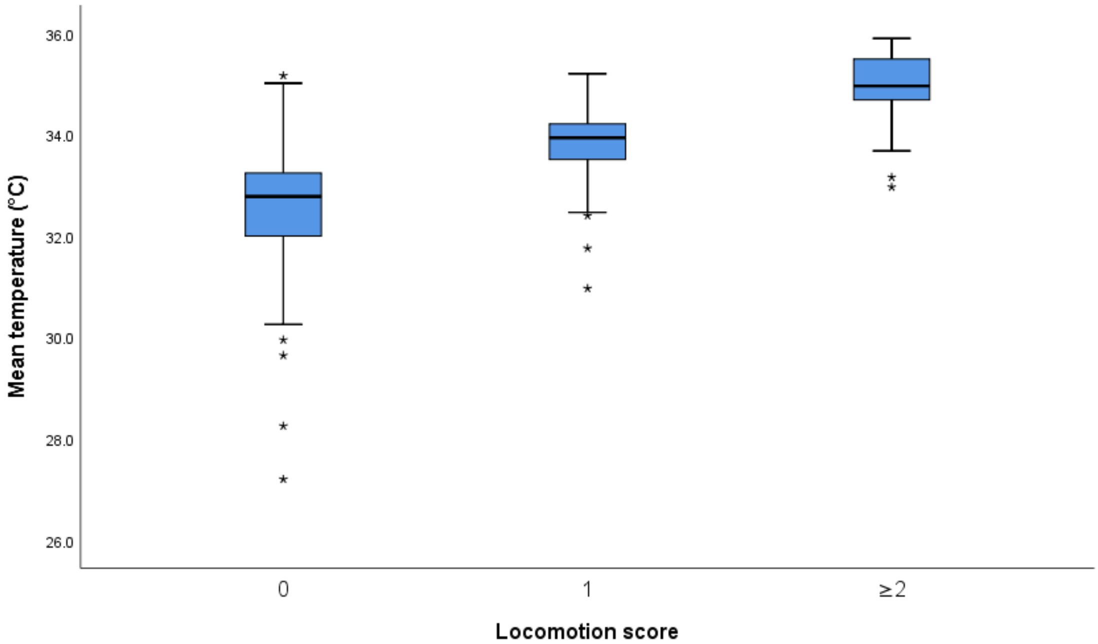

Figure 3. Boxplot of mean temperature (all zones, both feet) versus locomotion score (n = 215). Outliers are marked as asterisks.

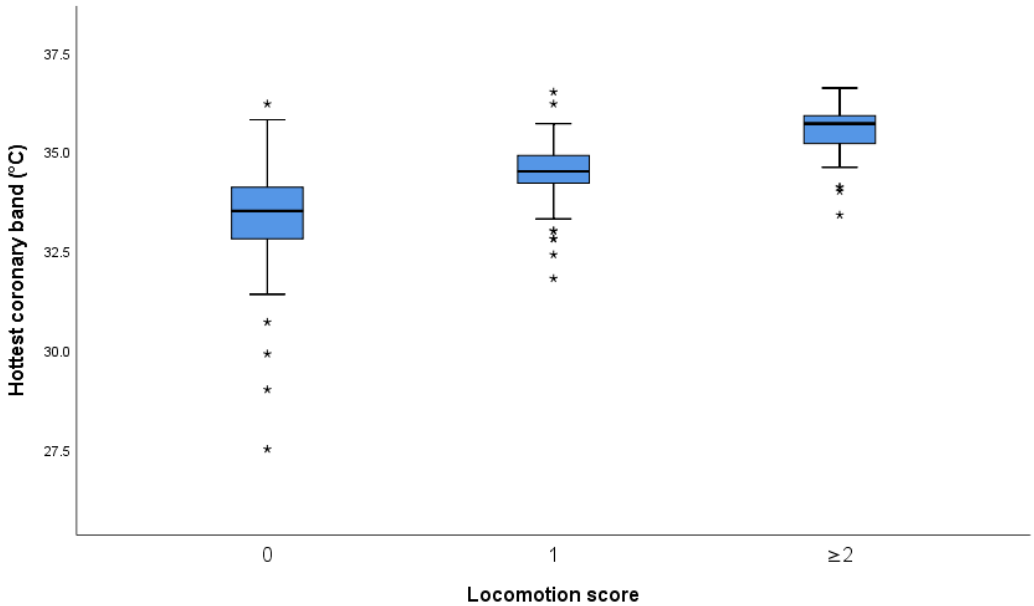

Figure 4. Boxplot of hottest coronary band temperature (zone 1 or 5) versus locomotion score (n = 215). Outliers are marked as asterisks.

Interpretation Figures 3 and 4 and Appendix B Figures A1–A4: The central box spans the quartiles, and the line in the box denotes the median. The line extends from the box (whiskers) to 1.5 times the interquartile range. Observations more than 1.5 times the interquartile range from the median are plotted individually as possible outliers (asterisks).

3.1.2. Association of Foot Temperatures and Locomotion Scores

There was a linear association between individual cow locomotion score and foot skin temperature for all six temperature measures. The data for MT and CB are presented in Table 4 and Appendix A Table A1 for the other four temperature measures. For MT, each one-unit locomotion score increase (assuming LS ≥ 2 was LS = 2) was associated with a 0.944 °C (95% CI: 0.781–1.141) rise in mean temperature. For CB, every one-unit increase in locomotion score was associated with a 1.067 °C (95% CI: 0.883–1.289) increase in the hottest CB temperature.

Table 4. Temperature measures estimates and their 95% confidence intervals (n = 215).

Model Parameter		95% Confidence Interval	
		Lower Bound	Upper Bound
Mean temperature (intercept)	34.877	34.614	35.140
Locomotion score *	0.944	0.781	1.141
Hottest coronary band (intercept)	35.483	35.199	35.768
Locomotion score *	1.067	0.883	1.289

* Effect of increase in locomotion score of 1 unit in DairyNZ lameness score (all score 3 cows recorded as score 2). See Table 2 for the definition of temperature measurement.

3.1.3. A Receiver Operating Characteristic (ROC) Analysis

ROC curves for MT and CB are presented in Figure 5 (see Appendix B, Figure A5 for other temperature measures). In addition, optimal threshold values, area under the curve, and calculated parameters for MT and CB temperature measures are summarised in Table 5 (see Appendix A Table A2, for the results for other temperature measures).

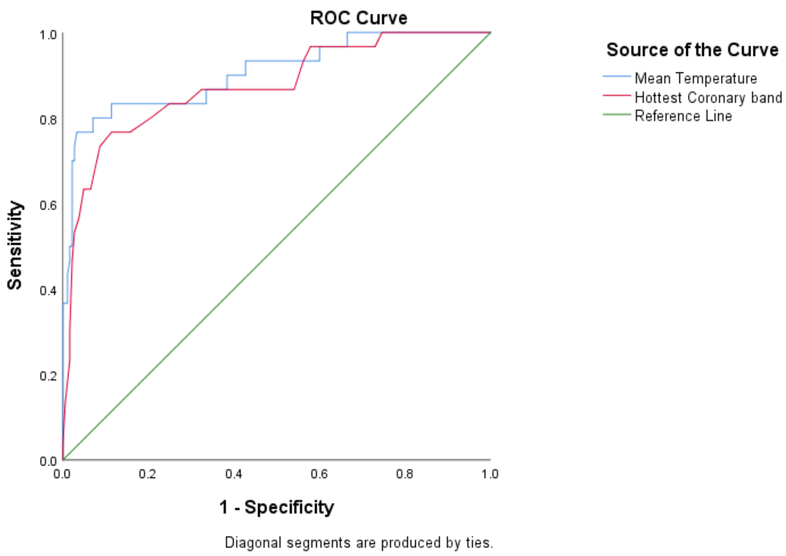

Figure 5. A receiver operating characteristic (ROC) curves; used to determine the optimal threshold values for the infrared thermography's sensitivity and specificity, assuming locomotion scores ≥ 2 as locomotion score = 2 (n = 215).

Table 5. Optimal cut-off points for skin foot temperature measurements (degrees centigrade) for determining lame cows (Dairy NZ lameness score ≥ 2).

Temperature Measure [1]	Optimal Threshold (°C)	AUC (95% CI)	Specificity (95% CI)	Sensitivity (95% CI)	PPV (95% CI) *	NPV (95% CI) *
Mean Temperature	34.5	0.91 (0.84–0.97)	92.4 (87.63–95.80)	80.0 (61.43–92.29)	63.3 (50.21–74.60)	96.6 (93.27–98.31)
Hottest coronary band	35.1	0.87 (0.80–0.95)	85.4 (79.48–90.16)	76.7 (57.72–90.07)	46.1 (36.42–56.07)	95.7 (92.14–97.73)

[1] See Table 2 for the definition of temperature measure; AUC, area under the curve; CI: confidence interval; PPV, positive predictive value and NPV, negative predictive value; (*, PPV and NPV calculated at a prevalence of 14%) analysis based on data from 215 cows.

4. Discussion

The present study aimed to evaluate the use of infrared thermography (IRT) as a tool for detecting lameness in a pasture-based dairy herd against the widely used visual locomotion scoring. IRT has been previously employed to detect foot lesions [32,36,40,44,48] and is associated with locomotion scores in housed cows [43,52]. However, the current study used IRT to detect gait changes (higher locomotion scores) in cows kept permanently at pasture.

4.1. Feasibility of Infrared Thermography as a Method on New Zealand Dairy Farms

For this study, thermal imaging of the plantar aspect of the foot was done alongside routine pregnancy diagnosis, without physical animal contact. However, even with the slowing down of the platform for pregnancy diagnosis, it was impossible to obtain an IRT image for every cow due to the time required to generate an image of the suitable quality of each foot. This is obviously a major limitation of the protocol, as to score an entire herd, IRT will need to be used on multiple occasions. However, in a pasture-based system, not all cows can be locomotion scored at one milking. The high flow rate of cows exiting the milking parlour makes it impossible to observe the gait of all cows and individually identify an observed cow's number [27]. Nevertheless, cows that are not recorded as having a locomotion score are much more likely to have locomotion scores of 0 or 1 because it is much easier to detect and identify lame and severely lame cows exiting the milking parlour than cows with no or minor gait changes. Thus to be used as an alternative to locomotion scoring, IRT needs to be much faster than it is currently. An automated imaging process from a fixed point would be faster. However, there would be challenges regarding picture quality as there will be no camera repositioning if the foot is not in focus.

One limitation of this study is that the imaging process only captured temperature measurements of hind feet. Although, in housed cattle, hind limb lameness accounts for more than 90% of dairy cows [53], in New Zealand, the proportion of lame cows with hindfoot lesions is lower (71 and 56% in cows and heifers, respectively [54]). In New Zealand, the proportion of lame cows with front foot lesions is higher (29 and 44% in cows and heifers, respectively [54]). Thus only measuring hind feet is likely to have reduced the sensitivity of IRT for detecting lameness. However, front foot lameness may increase foot skin temperature in the hind feet as the animals compensate for that lameness by increasing the weight borne by the hind limbs.

In addition, the IRT process may not detect cows that are lame due to non-hoof lesions (e.g., lesions of the hock or stifle). However, non-hoof-related lesions cause ~5% of lesions in lame dairy cattle in New Zealand, only [54]. Nevertheless, in the pasture-based production system that predominates in New Zealand, the only feasible time for collecting IRT images is during milking, when it is impossible to obtain high-quality images of the forelimbs easily and quickly. Therefore, further research on more cows and farms is required to establish how best to address these challenges and apply IRT in cows kept at pasture.

Cows' feet were not washed before IRT, as Stokes et al. [48] found no clinically significant difference between cleaned and dirty feet when using IRT. Furthermore, cleaning the feet would have significantly increased the time taken to obtain IRT images, further decreasing the proportion of the herd which could be imaged per milking. Nevertheless, several researchers have cleaned the feet before IRT in their studies [48,55,56]. Hence further research on the value of washing before IRT in pasture-based cattle is needed, particularly whether the benefit of washing changes during the season as cow dirtiness changes.

4.2. Skin Foot Temperature and Effect of Claw and Zone

In the present study, we used maximum temperatures within each zone for all the analyses as recommended for detecting lesions with IRT [48,49,57]. In addition, both hindlimbs were evaluated together as lameness-causing foot lesions can occur across both hind feet with equal likelihood. We found that lateral claws had a higher mean temperature than medial claws, though differences were small (highest difference of 0.1 °C between zones 3 and 7) (Figure 2). Other studies have reported larger differences in temperature between lateral and medial claws [34,58]. For example, Nikkhah et al. [34] reported that the temperature difference between the coronary band and area above the coronary band was 5.2 °C and 4.2 °C for lateral and medial claws, respectively, while Wilhelm et al. [58] reported mean temperatures of 18.6 °C and 16.9 °C for lateral and medial claws, respectively. However, both these studies were on trimmed feet, and Nikkhah et al. [34] recorded the temperature of the dorsal wall while Wilhelm et al. [58] recorded the temperature of the solear surface. In contrast, a recent study by Gianesella et al. [56] reported higher medial claw temperatures than lateral claw temperatures in both healthy cows and those with claw lesions. They reported that the difference between medial and lateral claws was 2.3 °C and 2.1 °C for healthy and diseased claws, respectively.

Our results showed that both lameness and claw zone position (medial or lateral) affected temperature. These findings suggest that the small observed temperature difference between claws may be related to hindlimb lateral claws being more prone to claw horn lesions [34,54,59] and thus may have reflected subclinical conditions of the claws, which were not yet apparent. Further research is required to test this hypothesis. The effect of the zone was the same across claws, e.g., zones 1 and 5 (coronary band) had higher temperatures than zones 2 and 6 (skin above the coronary band). These results are consistent with previous studies [32,34,60,61]. However, the mean temperature difference in the current study is small, with 0.48 °C being the largest difference between the coronary band and skin above the coronary band.

Temperature measurements for the other zones evaluated in the current study have not been frequently reported. However, considering the claws, zones 3 and 7 (below the accessory digits) had a higher temperature than both zones 2 and 6 (above the coronary band) and zones 1 and 5 (coronary band). Zone 4 (interdigital space) also had a higher temperature than the other zones within the foot.

The higher skin temperature measured in the interdigital space (zone 4) could be explained by anatomical features. This hairless area is highly vascularised, and skin from both claws meets at this point; therefore, friction could be generated between the two claws in this relatively confined area leading to a rise in skin surface temperature. However, it is also a potential location for diseases such as foot rot, interdigital dermatitis, interdigital hyperplasia, and digital dermatitis [62]. Therefore, recording the temperature of zone 4 may be a more specific means of detecting those infectious diseases than measuring the temperature of other zones. However, this needs further investigation under New Zealand conditions because the farm was free of digital and interdigital dermatitis during this study and had a very low prevalence of footrot, so it was not suitable for testing this hypothesis.

4.3. Infrared Thermography as a Predictor of Locomotion Score

Lameness prevalence (scores ≥ 2) of the cows examined in the present study was 14%. Although the current study did not include the lame group, this finding is within the range of results reported by Fabian et al. [23], who reported that lameness prevalence on 59 dairy farms across New Zealand ranged from 1.2 to 36% (mean 8.1%).

The present study revealed that median claw temperature increased as locomotion scores increased (Table 4). This is consistent with previous studies that have measured skin temperature in the same foot region as this study. For example, Lin et al. [52], who used a non-contact infrared thermometer on washed feet and measured the temperature of the skin in an area roughly equivalent to zones 2 and 6 in this study, reported that they were able to differentiate score 0 from score 1 and score 1 from ≥2 using their temperature measurements. However, not all results have been as clear. Rodríguez et al. [43], who used a thermal camera and measured skin temperature in the same area as Lin et al. [52], were able to separate cows with score 0 from cows with score 2 and score 3, but could not separate score 1 cows from cows with higher or lower locomotion scores. The mean skin temperatures recorded by [43] (after washing) were 20.2, 23.2, 24.8 and 25.9 °C for locomotion score 0, 1, 2, and 3, respectively, so this lack of differentiation may be a lack of power (as Rodríguez et al. [43] only had 30 cows per score group).

The present study used a cut-off of 34.5 °C for the mean temperature of all 14 zones, and this cut-off value maximised sensitivity and specificity at 80 and 92.4%, respectively (Table 5 and Appendix A Table A2). Thus, this cut-off point and the values for sensitivity and specificity are higher than previously reported figures by studies of IRT and LS. For example, Rodríguez et al. [43], using a cut-off of 25.5 °C, reported a sensitivity of 46.7% and specificity of 89.7%, while Lin et al. [52], using a cut-off of 23.3 °C, reported sensitivity of 78.5% and specificity of 39.2%. The sensitivity and specificity are also higher, though not so clearly than previous studies evaluating IRT and clinical lameness. For example, Main et al. [40], using a cut-off of 25.25 °C, reported a sensitivity of 72% and specificity of 73%, while Stokes et al. [48], with a cut-off of 27.0 °C, reported a sensitivity of 80% and specificity of 73%.

Nevertheless, even the high specificity reported in this study is not sufficiently high for IRT to be used as the sole screening method for identifying cows that require lameness treatment. In this population, the positive predictive value of IRT was <65%, i.e., 1/3 of cows predicted as having a locomotion score > 1 by IRT actually had a score ≤ 1. If cows identified as lame by IRT are progressed to lameness treatment without further observation such as LS, a significant amount of staff time will be wasted examining non-lame cows. If IRT were to be used for frequent, ongoing monitoring in a population (e.g., daily measurement), this issue would be even more significant as monitoring will reduce the number of unidentified lame cows. Therefore, increase the proportion of the herd that is not lame, and the proportion of false positives produced by IRT. For example, in a herd where no cows are lame, IRT will still identify on average 15 lame cows for every 200 cows examined (specificity = 92.4%).

One caveat to this discussion is that the calculation of sensitivity and specificity used in this study assumes that locomotion scoring is a gold standard when it is known that LS does not have 100% specificity or sensitivity [21,63,64]. This could be addressed by using a latent class analysis which does not assume that either LS or IRT are a gold standard. However, the authors are not aware of any latent class analysis of LS, and such an analysis is beyond the scope of this paper.

The comparison of specificity and sensitivity results highlighted the difference between the optimal temperature thresholds identified in this study and previous studies. Previous studies of IRT and LS and IRT and clinical lameness have identified a range of thresholds [36,40,43,44,48,52,55,56], but, as far as the authors are aware, this study's optimal cut-off is the highest reported. The difference between the threshold in this study and the highest previously reported threshold is much greater than the differences between previous studies. Some of this can be explained by differences in the protocol; e.g., both Rodríguez et al. [43] and Lin et al. [52] measured skin temperature after washing, but washing reduces temperatures by up to 2 °C [48], not than the 8–10 °C difference seen between the thresholds identified in the current study and those of previous studies. Thus other factors must be influencing at least some of the differences. These may include ambient temperatures, e.g., studies in the UK [36,40,48,62] were undertaken during the autumn/winter/spring seasons, while our study was conducted during summer. However, it is also possible that a key reason for the difference is that the cows in this study were all kept at pasture, whereas previous studies were undertaken in housed cows. Perhaps the main difference between these two systems is that cows at pasture are much more active in contrast to housed cows. In particular, the cows in this study will all have recently walked from the grazing area to the milking parlour. There have been no published data on the impact of such activity on foot skin temperature, but it is likely to have increased blood flow and, therefore, skin temperature. Further research is needed to understand better how walking affects temperature as there is significant variation in distance walked from pasture to the milking parlour within and between farms.

Nevertheless, even though we do not know exactly how walking distance affects foot temperature. It is another variable that needs to be considered when interpreting IRT results alongside other factors such as ambient temperature, recent rainfall, current weather, foot cleanliness, and lactation stage. All of these factors change day-to-day, and thus their effect could not be investigated in this study which was based on the analysis of results from a single timepoint. There are also likely to be significant differences between farms in many of these factors. It is thus likely that the optimal threshold temperature for IRT in cattle kept at pasture will not be consistent across farms or over time within a single farm. Further research across New Zealand on more farms for longer periods is required to identify how optimal IRT threshold changes and the key factors responsible for this change.

If thermal scanning does become feasible as an on-farm lameness detection method, its use will probably have to be based on repeated measurements on individual cows over time (which will necessitate some form of automation). Furthermore, these repeated IRT results will have to be combined with multiple inputs from other sources (such as weather stations). This practice will create a large dataset that is best analysed using a machine learning type process that can deal with within and between farm heterogeneity (such as classification by analysis which has just been used for diagnosing mastitis from a similarly complex dataset [65]).

5. Conclusions

Our results demonstrated that the plantar aspect of the hindfoot could be easily thermally imaged for measuring the hindfoot skin temperature. Therefore, this location can be used for assessing the presence of foot-associated lameness-causing lesions as it can evaluate multiple anatomical areas, including coronary band, surface skin above CB, interdigital space, and surface skin below the accessory digit. Furthermore, the results of the present study show that such measurements can be used to distinguish between cows with different locomotion scores such as score 0 (sound–cows that do not need attention with regards to lameness), 1 (imperfect gait–cows that need close observation), and $\geq$2 (lame cows that need treatment). Therefore, IRT has a considerable potential to be used on-farm to screen for lameness. However, the specificity of IRT observed in the current study does not appear high enough for IRT to be used as an alternative to locomotion scoring [66]. In addition, automation of the process will likely be necessary for IRT to be used without interfering with farm operations. This automation will also open the way for repeated skin temperature measurements, resulting in more accurate lameness detection than single measurements, especially if the IRT data are combined with other inputs in a machine learning process.

Author Contributions: C.W.W. and the supervisory team conceptualised the study. First, C.W.W. collected data and did the initial data analysis and exploration. Next, R.L. validated data analysis and suggested further analysis. C.W.W. and R.L. undertook the final analysis, and then C.W.W. wrote the first draft of the paper, which was contributed to and finally approved by all authors. L.L., K.M. and R.L. supervised the project. R.L. was responsible for funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The observation and image capture described in this study does not meet the definition of manipulation in the New Zealand Animal Welfare Act 1999. Therefore, ethical approval for animal manipulations was not required.

Informed Consent Statement: The farmer was a client of the Massey Farm Practice and when informed about this project was interested in participating.

Data Availability Statement: Data are available at request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Temperature measures estimates and their 95% confidence intervals (n = 215). Illustration: Hottest zone above the coronary band (ACB), hottest zone below the accessory digit (BAD) temperatures (n = 215).

Model Parameter		95% Confidence Interval	
		Lower Bound	Upper Bound
Hottest zone (intercept)	35.957	35.716	36.197
Locomotion score *	0.958	0.793	1.157
Hottest zone 4 (intercept)	35.590	35.280	35.900
Locomotion score *	1.218	1.008	1.471
Hottest ACB (intercept)	35.153	34.915	35.392
Locomotion score *	1.087	0.900	1.314
Hottest BAD (intercept)	35.657	35.385	35.929
Locomotion score *	1.126	0.932	1.361

* Effect of increase in locomotion score of 1 unit in DairyNZ lameness score (all score 3 cows recorded as score 2). See Table 2 for the definition of temperature measurement.

Table A2. Optimal cut-off points for skin foot temperature measurements (degrees centigrade) for determining lame cows (Dairy NZ lameness score $\geq$ 2). Illustrations: [1] See Table 2 for the definition of temperature measure; AUC, area under the curve; CI: confidence interval; PPV, positive predictive value and NPV, negative predictive value; (*, PPV and NPV calculated at a prevalence of 14%) analysis based on data from 215 cows.

Temperature Measure [1]	Optimal Threshold (°C)	AUC (95% CI)	Specificity (95% CI)	Sensitivity (95% CI)	PPV (95% CI) *	NPV (95% CI) *
Hottest zone	35.7	0.861 (0.799–0.923)	82.2 (75.87–87.39)	73.3 (54.11–87.72)	40.1 (31.46–49.39)	95.0 (91.24–97.17)
Hottest zone 4	35.2	0.790 (0.707–0.873)	72.4 (65.40–78.73)	73.3 (54.11–87.72)	30.2 (23.96–37.31)	94.4 (90.15–96.82)
Hottest zone ACB	35.1	0.914 (0.865–0.963)	95.7 (91.66–98.11)	60.0 (40.60–77.34)	69.3 (51.92–82.53)	93.6 (90.45–95.80)
Hottest zone BAD	35.1	0.893 (0.832–0.954)	82.2 (75.87–87.39)	83.3 (65.28–94.36)	43.2 (34.93–51.86)	96.8 (93.13–98.54)

Appendix B

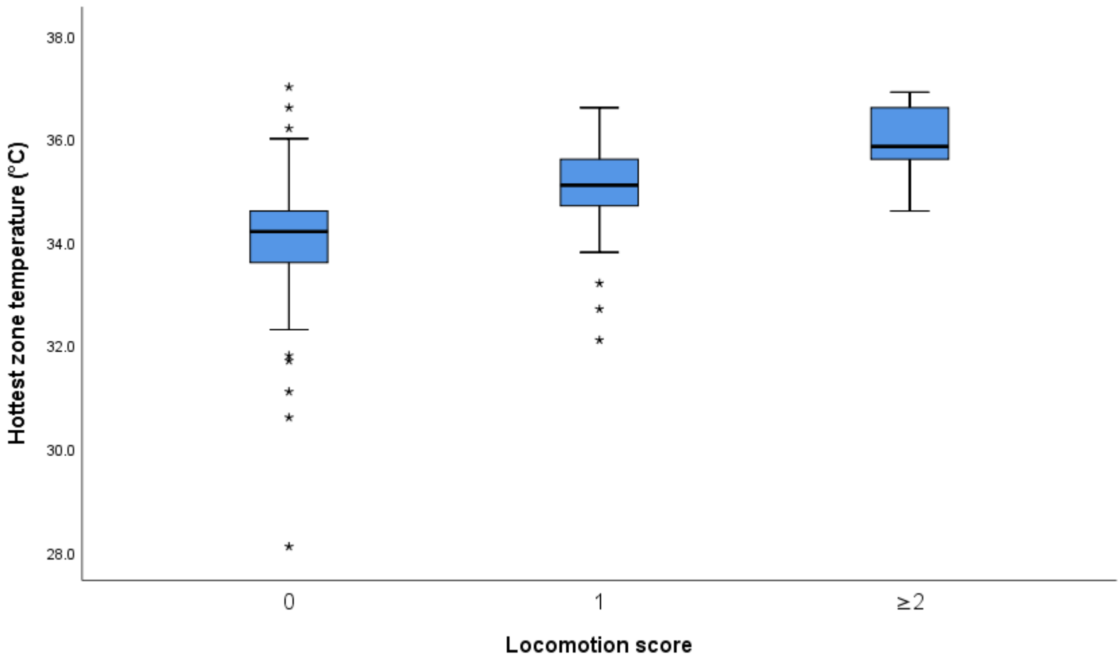

Figure A1. Boxplot of hottest zone temperature (out of all 14 zones) versus locomotion score (n = 215). Outliers are marked as asterisks.

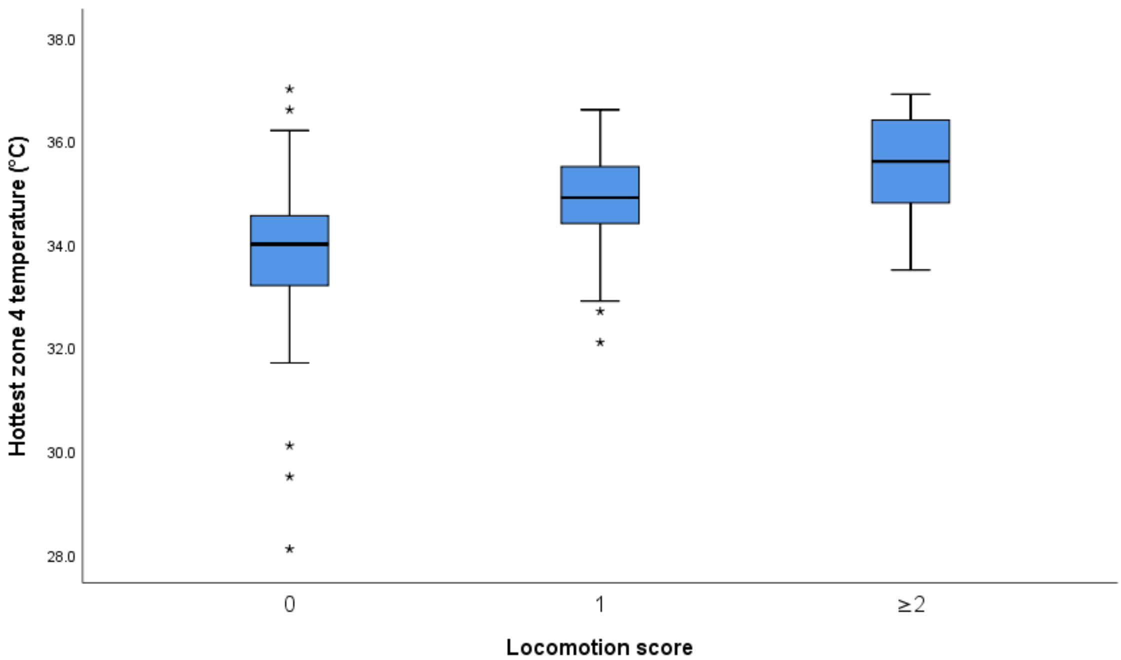

Figure A2. Boxplot of hottest zone 4 (interdigital space) versus locomotion score (n = 215). Outliers are marked as asterisks.

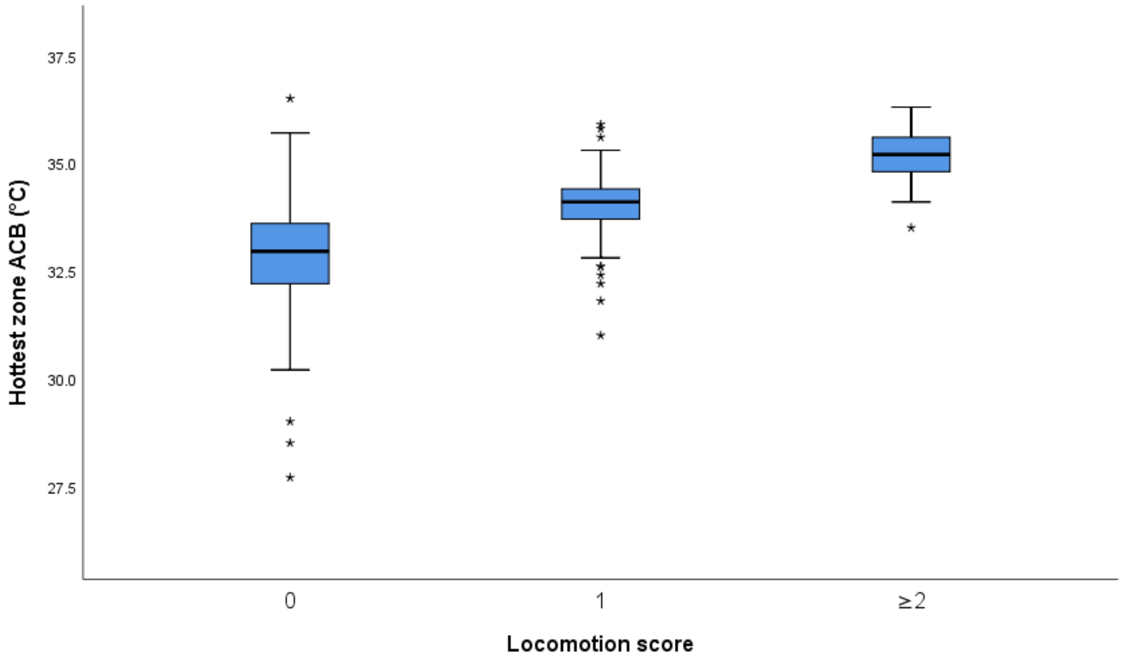

Figure A3. Boxplot of the hottest zone above the coronary band (zone 2 or 6) versus locomotion score (n = 215), ACB = above the coronary band. Outliers are marked as asterisks.

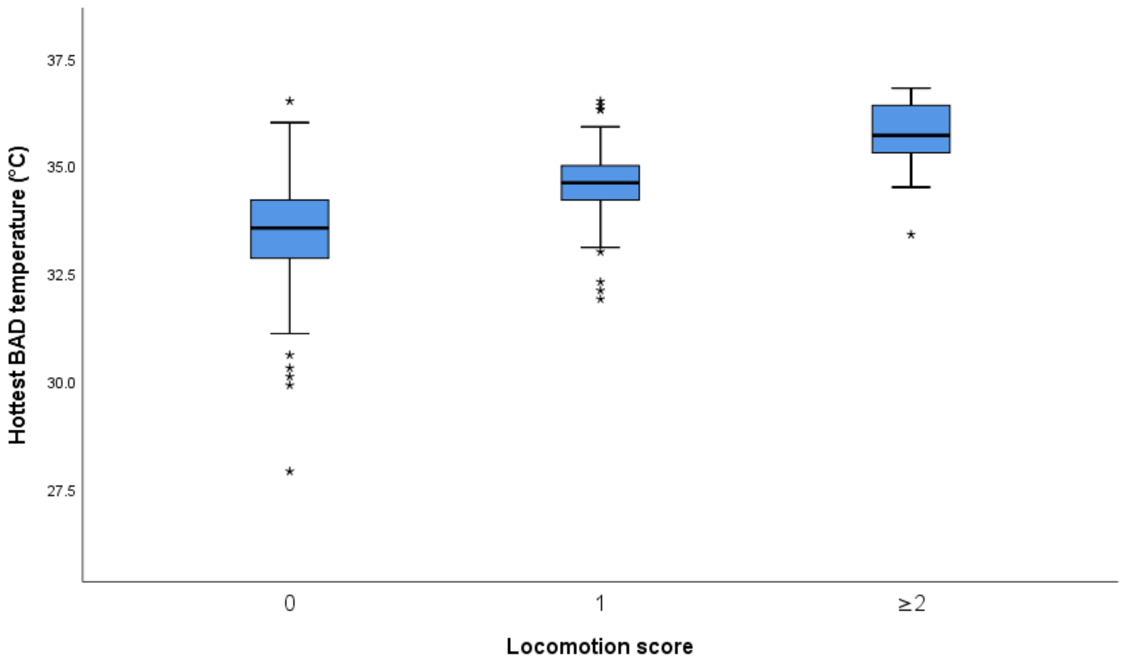

Figure A4. Boxplot of the hottest zone below the accessory digits (zone 3 or 7) versus locomotion score (n = 215), BAD = below the accessory digits. Outliers are marked as asterisks.

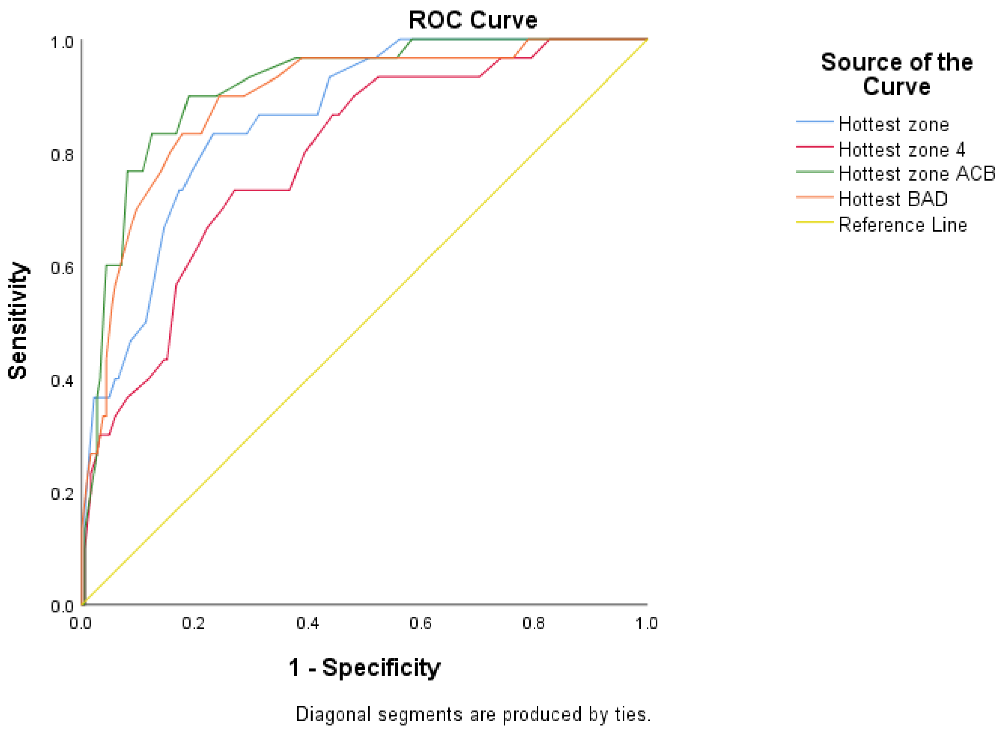

Figure A5. A receiver operating characteristic (ROC) curve; used to determine the optimal threshold values for the infrared thermography's sensitivity and specificity, assuming locomotion scores ≥ 2 as locomotion score = 2 (*n* = 215). ACB = above the coronary band, BAD = below the accessory digits.

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Chapter Four: Evaluating Alternatives to Locomotion Scoring for Detecting Lameness in Pasture-Based Dairy Cattle in New Zealand: In-Parlour Scoring

Foreword: This chapter covers the study that evaluated in-parlour scoring against locomotion scoring for lameness detection in dairy cows in pasture-based production systems in New Zealand. On two dairy farms on the Northern Island of New Zealand, throughout the production season of 2018/19, cows were scored fortnightly and recorded the presence of four indicators (shifting weight, abnormal weight distribution, swollen heel or hock joint, and overgrown hoof). Two or more indicators were more useful predictors of higher locomotion scores (lameness). The study has been published and can be accessed via this link: https://doi.org/10.3390/ani12060703. In this thesis, the article has been presented as it appears in journal format and style.

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Evaluating Alternatives to Locomotion Scoring for Detecting Lameness in Pasture-Based Dairy Cattle in New Zealand: In-Parlour Scoring

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Simple Summary: Lameness in dairy cows is a significant challenge globally. Early detection accompanied by effective treatment can reduce the number of cows that are lame and the impact of lameness. Currently, locomotion scoring by observing the gait posture of cows is the most widely used method of detecting lame cows. However, its use is limited, especially in pasture-based production systems like in New Zealand. One possible alternative to locomotion scoring is observing and recording cows for indicators of lameness while cows are being milked. We recorded the presence of four indicators (shifting weight, abnormal weight distribution, swollen heel or hock joint, and overgrown hoof) on two dairy farms in New Zealand. Two or more indicators were more useful predictors of higher locomotion scores (lameness). However, more results on more farms are needed before the in-parlour scoring procedure can be recommended as an alternative to locomotion scoring in pasture-based dairy cattle.

Abstract: Earlier detection followed by efficient treatment can reduce the impact of lameness. Currently, locomotion scoring (LS) is the most widely used method of early detection but has significant limitations in pasture-based cattle and is not commonly used routinely in New Zealand. Scoring in the milking parlour may be more achievable, so this study compared an in-parlour scoring (IPS) technique with LS in pasture-based dairy cows. For nine months on two dairy farms, whole herd LS (4-point 0–3 scale) was followed 24 h later by IPS, with cows being milked. Observed for shifting weight, abnormal weight distribution, swollen heel or hock joint, and overgrown hoof. Every third cow was scored. Sensitivity and specificity of individual IPS indicators and one or more, two or more or three positive indicators for detecting cows with locomotion scores ≥ 2 were calculated. Using a threshold of two or more positive indicators were optimal (sensitivity > 92% and specificity > 98%). Utilising the IPS indicators, a decision tree machine learning procedure classified cows with locomotion score class ≥ 2 with a true positive rate of 75% and a false positive rate of 0.2%. IPS has the potential to be an alternative to LS on pasture-based dairy farms.

Keywords: lameness; locomotion scoring; in-parlour scoring; decision tree; machine learning; pasture-based system; dairy cows

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1. Introduction

Early lameness detection is one of the most significant challenges in the dairy industry. The impact of delayed lameness detection and treatment is evident in terms of production losses [1–3], treatment costs [4], fertility problems [5–7], and health and welfare issues [8–10], as well as chronic irreparable claw damage [11].

Earlier detection accompanied by effective treatment would reduce the prevalence and impact of lameness [12]. However, early diagnosis requires effective detection methods that can be easily employed on the farm. Currently, locomotion scoring (LS) is the most commonly used method of lameness detection on-farm [13]. However, in pasture-based production systems such as those which predominate in New Zealand, opportunities for LS are generally limited to around milking time, with, ideally, the cows being observed as they exit the milking parlour after milking. This practice requires trained staff (in addition to those needed for milking) to stand outside the parlour exit for the whole of the milking session. However, in New Zealand, dairy farms are generally large with a high ratio of cows to staff (mean 146 cows per full-time equivalent staff member [14]). Thus, ensuring staff availability for LS during a period of high workload can be challenging to achieve. Additionally, especially on farms with herringbone parlours, it can be challenging to individually observe every cow when they leave the parlour because cows exit the parlour in batches. This difficulty is exacerbated by environmental factors, such as wind, sunlight, and rainfall, that the observer and cows might be exposed to during the scoring exercise. Consequently, there is a need for easy to use and effective lameness detection systems in pasture-based herds.

An alternative to visual LS would be to observe cows for indicators associated with lameness during milking. This practice could allow a staff member to milk and record lameness simultaneously, especially if the aim were to determine lameness prevalence in a herd (which requires scoring only part of the herd [15]) rather than individually identifying lame cows.

The critical problem with detecting lameness in cows during milking is that it is impossible to observe gait, which is crucial for most locomotion scores. However, the same problem arises when detecting lameness in cows in tie stalls. Leach et al. [16] developed a stall lameness score (SLS) protocol to detect lameness in tied cows using indicators/behaviours such as weight shifting, rotation of feet, standing on the edge of a step, resting of feet, and uneven weight-bearing. They compared lameness based on SLS, where a cow was defined as lame by the presence of two or more indicators on the screening list, with a 5-point scale [10] gait-based locomotion score. The study found that the SLS underestimated the proportion of lame cows compared to LS.

The study by Leach et al. [16] was a small one (including only 98 cows) and was thus more a proof of concept than a definitive test of the SLS value as a lameness measure. However, multiple studies have since used the SLS (or a modification) to assess lameness in dairy cows in tie stalls [17–22]. For example, both Gibbons et al. [22] and Palacio et al. [21] compared SLS using the indicators described by Leach et al. [16] except for foot rotation, with LS systems [23,24]. Both used the presence of two or more predictors to define a lame cow using SLS. However, while Palacio et al. [21] concluded that using SLS resulted in fewer cows recorded as lame, Gibbons et al. [22] reported that SLS overestimated lameness prevalence compared to LS. Nevertheless, both studies concluded that the SLS was a helpful measure of determining lameness prevalence at the herd level.

Another opportunity where standing cattle could be observed for lameness is when they are locked in stanchions. For example, Hoffman et al. [25] observed cows locked in stanchions for the presence/absence of an arched back, cow-hocked stance, widely placed hind limbs, and favouring a leg while standing. These individual indicators were compared with LS (Sprecher et al. [7]), with a locomotion score ≥ 3 on a 5-point scale used to define lameness. Hoffman et al. [25] concluded that observation of cattle locked in stanchions lacked sufficient sensitivity or specificity to be used as an alternative to LS. However, they suggested that observing these indicators may be useful as a screening test for identifying cows requiring a further examination for lameness.

García-Muñoz et al. [26] also investigated the association between postural and gait abnormalities observed in cows locked in stanchions utilising the same indicators and lameness definition as [25]. Consistent with Hoffman et al. [25], they concluded that the sensitivity of lameness detection in stanchions was too low for it to be used as an alternative to standard LS.

These studies suggest that non-locomotory lameness assessments may be a suitable method for identifying cows that need to be more closely examined for lameness or for estimating lameness prevalence in a herd. However, none of these studies has been undertaken in pasture-based dairy cattle during milking in rotary parlours. The latter is important, as rotary parlours tend to be used in larger herds where the number of cows per full-time staff member is higher [27], increasing the value of alternatives to standard LS. Nevertheless, not all indicators proposed by Leach et al. [16] can be assessed effectively in cows milked in rotary parlours, particularly evaluating uneven weight-bearing while moving the cow from side to side or standing on the edge of a stall. Thus, we need additional new indicators that can be assessed by observation only for in-parlour scoring. Potential indicators include back-arching [25,26], overgrown hooves [28–30], claw injuries [31,32], swelling of hock or heel [33,34] and swelling around the coronary band [35]. These indicators could be used alongside abnormal weight distribution and shifting weight to score the risk of lameness in the milking parlour. Therefore, this study aimed to assess the feasibility of observing these indicators during milking and compare this in-parlour scoring (IPS) procedure with whole herd LS in pasture-based dairy cows.

2. Materials and Methods

2.1. Animals and Farm Location

This study was conducted in two dairy farms located in the Manawatu region on the North Island of New Zealand. Both farmers were clients of the Massey University Farm Practice, and they were interested in participating in this project. Both farms used a rotary milking parlour and milked cows twice daily. On both farms, animals were kept at pasture permanently, and cows were given a small amount (~1 to 2 kg/cow) of additional feed at milking time. Hoof trimming and LS were not routine management practices on either farm. However, as part of another study, 250 cows were assessed and trimmed as required by a professional hoof trimmer on two occasions while the current study was being undertaken on farm 1. Lame cows were identified by farm staff when they were brought in for milking.

Farm 1: This farm had 1200 dairy cows available for study, with spring and autumn calving groups. Most cows were Friesian and Jersey crossbreds, with approximately 10% Friesian cows. Cows' age ranged from 2 to 10 years, with a mean age of 4 years. The milking herd was managed as two groups and milked twice daily through a 60-unit rotary milking parlour. Each group was milked in succession and grazed on separate paddock rotations within the same farm. On this farm, routine lame cow management involved regular veterinary visits every two weeks to treat lame cows, maintaining a lame-cow group kept close to the milking parlour and milked once a day in the morning. The lame-cow group was not included in this study as all farm visits were in the afternoons. According to on-farm treatment records of 50 lameness cases throughout the lactation season, the leading causes of lameness were white line disease (54%), sole injury (16%) and foot rot (8%). No digital dermatitis was diagnosed at any time.

Farm 2: This farm had 400 dairy cows calving in spring; approximately 95% were Jersey cows, with Friesian and crossbreds accounting for 5%, with an average age of six years. This farm used a 44-unit rotary milking parlour, managed the milking herd in two groups, and grazed in separate rotations on the same farm. However, there was no independent lame group (all lactating cows were milked twice daily). Lame cows were routinely treated by the farmer, with cows receiving veterinary services on request. According to on-farm treatment reports of 29 lameness cases across the lactation season, the leading cause of lameness was white line disease (72.4%). No digital dermatitis was detected at any time during the study.

2.2. Locomotion Scoring

Prior to the study commencing in August 2018, the first author (a veterinarian) was trained in LS. The training consisted of observing training videos created by DairyNZ [36] and Agriculture and Horticulture Development Board (AHDB) [37], followed by supervised LS on-farm (live cows) with a trained and experienced observer until the trainer was satisfied that the trainee could perform LS effectively. Inter-observer agreement between trainer and trainee was substantial (kappa = 0.870; 95% CI: 0.771–0.926). Cows were scored as they left the parlour after milking. The LS evaluation area was a flat concrete surface about 20 m in length, a walking distance sufficient for the assessment of animals' gait and posture attributes while they were exiting the milking parlour.

Locomotion was scored by the first author using the DairyNZ lameness score. This scoring system has been adapted from the Agriculture and Horticulture Development Board AHDB mobility score to create a system that can be used to score cattle when they are walking back to pasture after being milked [38]. The DairyNZ lameness score is based on the co-assessment of walking speed, walking rhythm, weight-bearing, back alignment, head position, stride length, and foot placement on a 4-point scale from 0 to 3 (Table 1).

Table 1. The description of locomotion scoring according to the DairyNZ system [39].

Score	Clinical Term	Evaluation Criteria
0	Sound	The cow walks confidently, even weight-bearing and tracks up.
1	Imperfect locomotion	The cow walks unevenly, does not track up, with a mildly arched back when walking.
2	Lame	An arched back, the favoured limb moves faster than the lame leg, feet placed unevenly, head bobs up and down when walking.
3	Severely lame	They walk very slow, reluctant to bear weight, arched back, and head bobs obvious.

Data were collected monthly on both farms, with whole herd LS being carried out a day before the in-parlour scoring procedure. This study was undertaken from August 2018 (start of lactation) until the end of that lactation season (April 2019). Farmers received feedback regarding cows identified as lame by LS.

2.3. In-Parlour Scoring (IPS)

Due to the rotary platform's high speed (10 min for one rotation) during milking, it was not possible to score every individual cow. Consequently, every third cow's hind limbs were observed (at a distance of ~1 metre) during afternoon milking and visually screened for the presence or absence of the prepared checklist of indicators, summarised in Table 2.

Table 2. The checklist of indicators that were put forward for use during the in-parlour scoring procedure (identified from the literature).

Indicator	Description
Shifting weight (SW)	Frequent changing of feet, i.e., twice or more per 30 s
Abnormal weight distribution (AWD)	The asymmetric placing of the claws on the ground
Swollen heel or hock joint (SHH)	Abnormal swelling of the heel and surrounding tissues (observed from the plantar aspect of the foot) or hock joint
Overgrown hoof (OH)	Irregular growth of claw capsule on at least one hind limb
Observed claw injury (OCI)	Observation of claw injury of any type, i.e., bruises, cuts
Swelling/separation around the coronary band (SCB)	Abnormal swelling or separation around the coronary band
Arched back (AB)	Arching of the back while standing

2.4. Statistical Data Analyses

Initially, all data were processed using an Excel spreadsheet (Microsoft, Seattle, WA, USA). Then, data were put forward for analysis only from cows with a locomotion score followed the next day by an in-parlour score. We used SPSS version 25 (IBM Corporation, Armonk, NY, USA) for all analyses except where stated otherwise. Descriptive statistics were created for each dataset. The correlation between the presence/absence of an IPS indicator and the other IPS indicators and the presence/absence of locomotion scores ≥ 2 was assessed using the Phi correlation coefficient to ensure there was no collinearity. Then for each individual IPS indicator and the presence of at least one, at least two, and at least three positive IPS indicators, the sensitivity, specificity, positive and negative predictive values for predicting locomotion scores ≥ 2 were calculated (MedCalc Version 19.5.1; MedCalc Software, Ostend, Belgium).

The ability of IPS to predict actual locomotion score (0, 1 or $\geq$2) was then analysed using a decision tree (DT) machine learning method. This was implemented using Scikit-learn—a machine learning library for the Python programming language [40]. The DT method was used to classify a cow observation into a locomotion score class based on the input of the IPS indicators. For this analysis, the amount of information that a specific IPS indicator conveyed was measured using Gini impurity. During the training process, splits were chosen by maximising the decrease in the Gini impurity (which is calculated by subtracting the weighted impurities of the branches from the original impurity). If a node (decision point) is entirely pure, i.e., observations are all classified into one class of locomotion score, then Gini impurity equals 0, no further splits will be performed. For this training process, the data were randomly split into four folds, with each fold containing approximately 25% of the entire observations.

The locomotion scores in one fold were kept as close as possible to the other folds, approximating the distribution of the locomotion scores estimated based on the entire observation set. One fold was held out as a test set, while the remaining three were used as a training set. This procedure was repeated four times, with each of the folds used once as test data (4-fold cross-validation). For each pair of training and test datasets, one DT was firstly grown to its maximum depth, i.e., no more splits at nodes were available (leaf nodes were pure or all IPS indicators had been used in a branch). The DT was then pruned based on the following criteria: (1) >20 observations were required to split an internal node, and (2) a split at a node had to decrease Gini impurity by at least 0.005. The value of 0.005 was chosen to balance the classification accuracy and the complexity of a DT. A shallow DT can lead to inaccurate classification, while a deep DT can give unreliable classification (i.e., the number of observations in a node is small or a split results in two nodes where the decision is made based on the one with a slightly larger number of observations).

The known locomotion score (recorded by the first author) and predicted locomotion scores from each DT classifier were then identified and organised into confusion matrices which were used to calculate the test accuracy for each DT classifier. The test accuracy is the proportion of all the observations in the test data that are correctly classified (i.e., the ratio of true positives and true negatives to the total number of observations). The DT classifier with the highest test accuracy was chosen for further interpretation and visualisation, and the true and false positive rates and precision were calculated for that DT classifier. True positive rate is the proportion of observations correctly classified into a specific class (i.e., ratio of true positives to the total of true positives and false negatives). It is equivalent to sensitivity (although it is important to notice that this is the sensitivity of a classifier, not of an individual IPS scoring method). False positive rate is the proportion of observations that were incorrectly classified into a particular class (i.e., ratio of false positives to the total of false positives plus true negatives). It is equivalent to 1—specificity (of a classifier, not of an individual IPS scoring method). Precision is the proportion of observations identified as belonging to a class that were correctly classified into that class (i.e., ratio of true positives to the total of true and false positives).

3. Results

3.1. Locomotion Score Distribution

The distribution of locomotion scores (which had matching in-parlour scores) for each visit to both farms is presented in Table 3. As score 3 cows were scarce (<0.3% of all scores), data from score 2 and score 3 cows were amalgamated (locomotion scores $\geq$ 2/lame cows). The data for each in-parlour scoring indicator on both farms are summarised in Table 4.

Table 3. Locomotion score of cows with the in-parlour scoring results available for both farms. The number of observations per farm was 3006 on farm 1 and 1119 on farm 2.

Month	Farm 1: LS				Farm 2: LS			
	LS 0	**LS 1**	**LS 2**	**LS 3**	**LS 0**	**LS 1**	**LS 2**	**LS 3**
August	220	82	8	0	73	31	4	0
September	226	95	5	0	70	43	5	0
October	228	101	8	1	67	50	3	1
November	240	85	10	1	89	32	5	0
December	254	86	10	0	93	24	5	0
January	246	81	12	2	87	36	5	1
February	260	63	9	0	80	39	4	1
March	261	66	9	0	89	42	3	0
April	197	122	15	3	93	41	3	0
Total	**2132**	**781**	**86**	**7**	**741**	**338**	**37**	**3**
% of the total by farm	**70.9**	**26.0**	**2.9**	**0.2**	**66.2**	**30.2**	**3.3**	**0.3**

LS = locomotion score; total denotes the sum of locomotion scores.

Table 4. Distribution of in-parlour scoring indicators with a locomotion score available. The number of observations per farm was 3006 on farm 1 and 1119 on farm 2.

Month	In-Parlour Scoring Results—Farm 1											
	SW0	**SW1**	**AWD0**	**AWD1**	**SHH0**	**SHH1**	**OH0**	**OH1**	**Total0**	**Total1**	**Total2**	**Total3**
August	284	26	280	30	294	16	274	36	222	72	14	2
September	297	29	286	40	312	14	287	39	215	102	7	2
October	311	27	312	26	308	30	297	41	230	92	16	0
November	318	18	314	22	314	22	281	55	235	86	14	1
December	320	30	324	26	339	11	303	47	251	86	12	1
January	315	26	315	26	323	18	297	44	243	82	16	0
February	317	15	315	17	323	9	287	45	256	67	8	1
March	311	25	313	23	328	8	296	40	251	75	9	1
April	299	38	290	47	320	17	268	69	191	124	19	3
Total	**2772**	**234**	**2749**	**257**	**2861**	**145**	**2590**	**416**	**2094**	**786**	**115**	**11**
% of total	**92.2**	**7.8**	**91.4**	**8.6**	**95.2**	**4.8**	**86.2**	**13.8**	**69.6**	**26.2**	**3.8**	**0.4**
	In-parlour scoring results—farm 2											
August	102	6	100	8	100	8	88	20	70	34	4	0
September	114	4	106	12	108	10	80	38	61	51	5	1
October	111	10	111	10	112	9	86	35	64	52	3	2
November	121	5	121	5	114	12	104	22	88	33	4	1
December	117	5	116	6	114	8	104	18	91	26	4	1
January	118	11	117	12	124	5	107	22	87	35	6	1
February	116	8	108	16	117	7	97	27	76	38	10	0
March	124	10	122	12	128	6	108	26	88	39	6	1
April	129	8	123	14	131	6	108	29	88	43	4	2
Total	**1052**	**67**	**1024**	**95**	**1048**	**71**	**882**	**237**	**713**	**351**	**46**	**9**
% of total	**94.0**	**6.0**	**91.5**	**8.5**	**93.7**	**6.3**	**78.8**	**21.2**	**63.7**	**31.4**	**4.1**	**0.8**

SW0 = weight shifting absent, SW1 = weight shifting present, AWD0 = abnormal weight distribution absent, AWD1 = abnormal weight distribution present, SHH0 = swollen heel or hock joint absent, SHH1 = swollen heel or hock joint present, OH0 = overgrown hoof absent, OH1 = overgrown hoof present. Total means number of positive indicators observed. Total0 = no positive indicator observed, Total1 = only one positive indicator observed, Total2 = two positive indicators observed, Total3 = three positive indicators observed. No cow on either farm was observed with four positive indicators.

Of the seven potential indicators identified in Table 2, three were not found to be useful in the present study analysis because of the following: Firstly, only one cow was observed with a bruise/cut on the claw during the entire study period, so this indicator was excluded from the analysis. Additionally, swelling around the coronary band was not easily observed in either parlour due to poor light conditions and dirty feet. Finally, back arching was not easily detected as the milking platforms were too high compared to the observer's eye line. This left four scoring indicators: shifting weight (SW), abnormal weight distribution (AWD), swollen heel or hock joint (SHH) and overgrown hoof (OH).

3.2. Assessment of the Association between the In-Parlour Scoring Indicators and Locomotion Score

Phi coefficients for the association between the presence/absence of the IPS indicators and LS are presented in Table 5. The strength of the association between the four IPS ranged from negligible to weak [41]. In contrast, the Phi coefficients indicated that the association between the in-parlour scoring indicators and locomotion score ≥2 was relatively strong for all four indicators [41] (Table 5).

Table 5. Phi coefficients for association between presence/absence of in-parlour scoring (IPS) indicators, and presence/absence of other in-parlour scoring indicators, and locomotion scores ≥ 2. (4125 paired observations across two farms; *n* = 3006 on-farm 1 and 1119 on-farm 2).

IPS Indicators	LS	SW	AWD	SHH	OH
SW	0.405		−0.029	0.127	−0.053
AWD	0.429			0.103	−0.040
SHH	0.490				0.041
OH	0.572				

LS = locomotion score, SW = shifting weight, AWD = abnormal weight distribution, SHH = swollen heel or hock joint, OH = overgrown hoof.

3.3. Sensitivities, Specificities, and Other Test Measures

The sensitivity and specificity for predicting LS ≥ 2 of the four individual indicators and thresholds of 1, 2, and 3 indicators are shown in Table 6. Sensitivity and specificity data separated by the farm are presented in Appendix A Table A1. Using the presence of two IPS indicators to predict LS ≥ 2 maximised specificity and sensitivity (>98% and >93%, respectively, Table 6).

Table 6. Sensitivity and specificity with 95% confidence interval for detecting locomotion score ≥2. Data amalgamated across farms (*n* = 4125).

IPS Indicators Present	Sensitivity	Specificity	PPV	NPV
SW	42.1 (33.6–51.0)	93.9 (93.1–94.6)	18.6 (5.3–22.4)	98.0 (97.7–98.3)
AWD	47.4 (38.7–56.2)	92.8 (91.9–93.6)	17.9 (15.0–21.2)	98.1 (97.8–98.4)
SHH	76.7 (68.6–83.6)	97.1 (96.6–97.6)	47.2 (42.2–52.3)	99.2 (98.9–99.4)
OH	42.9 (34.3–51.7)	85.1 (83.9–86.2)	8.7 (7.2–10.6)	97.8 (97.5–98.1)
One or more (≥1)	100.0 (97.3–100.0)	70.3 (68.8–71.7)	10.1 (9.7–10.5)	100.0
Two or more (≥2)	93.2 (87.5–96.9)	98.6 (98.2–98.9)	68.5 (62.6–73.9)	99.8 (99.6–99.9)
Three (3)	15.0 (9.4–22.3)	100.0 (99.9–100.0)	100.0	97.3 (97.1–97.4)

SW = shifting weight, AWD = abnormal weight distribution, SHH = swollen heel or hock joint, OH = overgrown hoof, PPV = positive predictive value, NPV = negative predictive value. Note that results for each farm separately are presented in Appendix A Table A1.

3.4. Association of In-Parlour Scoring Indicators and Locomotion Scoring (Decision Tree Method)

The DT was used to classify cows into different locomotion scores based on observed IPS indicators. The DT with the highest accuracy is visualised in Figure 1. This classifier correctly classified 995/1030 (96.6%) of cow observations into locomotion score class recorded by the first author. For each locomotion score, the number of cow observations correctly and incorrectly classified are summarised in Table 7. For example, no lame or severely lame cow (locomotion scores ≥2) was classified as sound by the DT, and similarly, no cow with a locomotion score of 0 was classified as lame or severely lame with the DT.

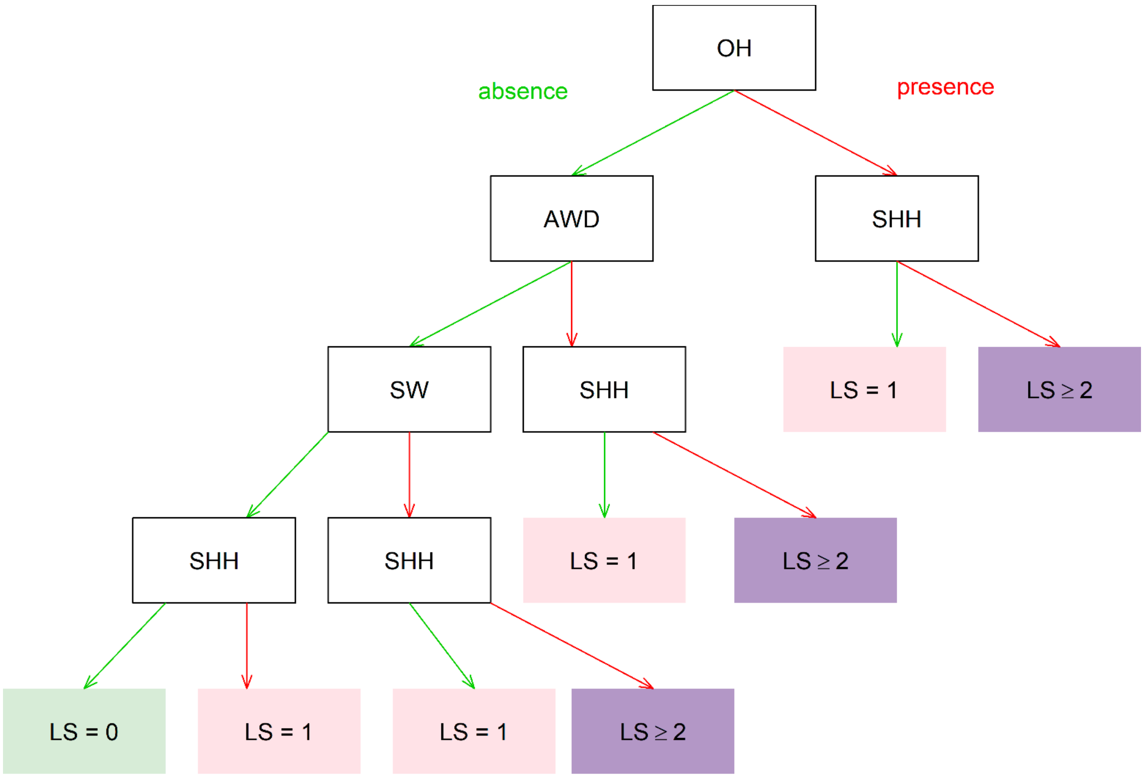

Figure 1. A decision tree to classify cows into different locomotion scores using observed in-parlour scoring indicators (n = 3095). n: the number of observations in the training set. Illustration: The green arrow from the root node pointed to the internal node when the indicator was absent. In contrast, the red arrow pointed to the internal node when the indicator was present. LS = locomotion score, SW = shifting weight, AWD = abnormal weight distribution, SHH = swollen heel or hock joint, OH = overgrown hoof.

Table 7. Confusion matrix of the decision tree classifier with the highest test accuracy calculated based on a test set including 1030 observations.

	Classified by Optimal Decision Tree Classifier		
Locomotion Score	**Sound**	**Imperfect Gait**	**Lame or Severely Lame**
Sound (0)	697	21	0
Imperfect gait (1)	4	274	2
Lame or severely lame (≥2)	0	8	24

True positive rate (TPR) and false positive rate (FPR) were lowest for locomotion score ≥2 and highest for locomotion score 1. In contrast, precision was lowest for locomotion score 1 and highest for locomotion score 0 (summarised in Table 8).

Table 8. True positive and false-positive rates and precision of the decision tree classifier with the highest test accuracy calculated based on a test set including 1030 observations.

Locomotion Score	True Positive Rate	False Positive Rate	Precision
0	97.1%	1.3%	99.4%
1	97.9%	3.9%	90.4%
≥2	75%	0.2%	92.3%

4. Discussion

The present study aimed to evaluate the potential of the in-parlour scoring (IPS) technique for detecting lameness in pasture-based dairy farms compared to visual LS. This is a preliminary study with a single observer on only two dairy farms, so further research is required. However, starting from seven indicators, we identified five indicators that were measurable while cows were being milked; four of these were shown in the subsequent analysis to be useful predictors of locomotion score.

The proportion of lame cows seen in the present study was consistent with previous reports of lameness in New Zealand. Lameness prevalence (percentage of locomotion scores ≥ 2) was 3.1 and 3.6% for farms 1 and 2, respectively (Table 3). These results are consistent with the range of prevalence reported by Fabian et al. [38], with the caveat that the true prevalence of high locomotion scores would have been greater on Farm 1 as no cows in the lame group were scored. However, the number of lame cows in the lame cow group was always <10 during the study. In addition, the pattern of lameness over a lactation season on both farms was similar to that reported by Lawrence et al. [42], who reported that the peak clinical lameness occurred during winter and the late spring for autumn-calving and spring-calving cows, respectively.

4.1. Feasibility of IPS

The present study's main challenge was the rotary milking platform's high speed (10 min for one rotation). As a result, there was insufficient time to screen all milking cows using IPS; however, it was simple to record the identity of all screened cows. In contrast, it was simple to locomotion score most (though not usually all) cows walking back to pasture after milking in a rotary parlour, but accurately identifying scored cattle was difficult. In fact, if identification is required (e.g., if the scoring is being used to identify cows for treatment), the proportion of cows that can be scored during a single milking is significantly reduced with LS compared to IPS. Thus, although the IPS technique takes more time per cow than LS, the ease of identification, combined with IPS not needing additional staff during milking, may mean that extra time per identified lame cow is similar for IPS and LS. However, further investigation on more herds, including farms with herringbone parlours (where in-parlour identification may be more difficult), is required to test this hypothesis.

Of the seven potential indicators included in the IPS at the start of this study, three indicators were not progressed to the analysis. Only one cow was observed with a bruise/cut on the claw during the entire study period; too few observations for inclusion in the analysis. Further research on more farms is required to identify whether this low level of claw injury is typical of New Zealand dairy farms. If it is, then observed claw injury would be unsuitable for in-parlour lameness scoring, although an observed claw injury indicator may be useful to record when cases are seen. Parlour design meant that arching of the back could not be observed on either farm as the observer had to stand below the level of the cows. On some rotary parlours, an observer can stand at the level of cows, and in herringbone parlours, the elevation of the cow may not be such an issue. So further investigation of the back arch as an in-parlour indicator of lameness in pasture-based dairy cattle is warranted. In addition, poor light conditions and dirty feet limited the observation of coronary band swelling. Therefore, it would be necessary to use a technique similar to that used by Yang et al. [43] to detect digital dermatitis lesions, i.e., wearing a head torch and washing the feet of all cows before scoring, to check effectively for coronary band swelling. Using this technique would increase the detection of digital dermatitis lesions but would undoubtedly increase the time taken for the IPS procedure. Therefore, further research is required to establish whether including observation of coronary band swelling improves IPS as an alternative to LS in herds where digital dermatitis is expected, as in New Zealand, is currently an extremely rare cause of lameness [43].

4.2. Assessment of IPS as a Method of Detecting Lame Cows

The four IPS indicators used in the analysis were independent of each other (phi < 0.13); thus, they provide different sources of information and, therefore, can usefully be used together as predictors of locomotion score. Individual indicators all had poor sensitivity for detecting locomotion score ≥ 2 (<50%), except for SHH, which had a moderate sensitivity of 77%. In contrast, specificity was high >90% for all indicators except OH, with a specificity of 85% (see Table 6). These findings are consistent with the conclusions of previous studies undertaken in tie-stall production systems that one indicator alone was not suitable for lameness detection [16,21,22]. Thus, as in those previous studies, we combined indicator scores to optimise lameness detection. Our analysis showed that using at least two positive IPS indicators was optimal (maximising sensitivity plus specificity). This result is consistent with previous studies [21,22] that also found that the presence of two or more indicators was optimal for identifying lameness in cows in tie stalls. However, our specificity and, in particular, sensitivity were better than reported in those studies, with Gibbons et al. [22] reporting a sensitivity of 63% and a specificity of 77%, and Palacio et al. [21] a sensitivity of 59% and a specificity of 90%, whereas we found a specificity of 98% and a sensitivity of 93%. In contrast, Leach et al. [16] concluded that optimal accuracy was obtained either when at least two of their indicators were positive or when any one indicator was present (excluding foot rotation). However, they reported specificity of ≥93% and sensitivity of ≤68% using at least two indicators to determine lame cows.

Our higher specificity and sensitivity compared to stall lameness scoring in tie stalls [16,21,22] may, in part, be related to the present study being undertaken in cows during milking without any physical contact, whereas stall lameness scoring involves physical contact to push the cow from one side to another. Physical handling produces stress which may reduce observed pain-related behaviours [44]. However, it is also likely that differences in our indicators could be responsible as of our four indicators; two (SHH and OH) were not used by previous studies [16,21,22]. Nevertheless, this study was performed on only two farms, so further research on more farms is required to better establish the sensitivity and specificity of IPS as a method for detecting locomotion scores ≥ 2.

In addition to analysing the ability of IPS to discriminate between lame and non-lame cows, we used a simple machine learning process to estimate how effective IPS was at classifying whether a cow had a locomotion score of 0, 1 or ≥2. As this process maximised accuracy across all three classifications, the results are different from the conventional analysis, which maximised accuracy for separating cows with a locomotion score of ≥2 from cows with other locomotion scores. Nevertheless, for locomotion scores 0 and 1, we obtained high sensitivity (or TPR) and high specificity (1-FPR). For locomotion score ≥ 2, specificity was extremely high (99.8%), but sensitivity was only moderate (75%). The difference between the two analyses is that the conventional analysis classified a cow with a locomotion score of ≥2 based on any two indicators; the decision tree classified any cow where SHH was absent as having a maximum locomotion score of 1 (see Figure 1).

As in our previous study with infrared thermography [45] and other studies which have evaluated similar scoring systems [16,21,22], we have used LS as a 'benchmark' to define lameness, although it does not have 100% specificity or sensitivity [23,24,46]. Thus, the differences between LS and IPS (or stall lameness scoring (SLS)) could be due to LS (even when correctly recorded) incorrectly categorising lame cows rather than errors in the other systems. In the present study, lameness prevalence based on two or more IPS indicators was higher than that recorded using LS (4.6% vs. 3.4%, respectively). However, this result was consistent over both farms (Appendix A Table A1). If these apparent false positives reflect cows that will become lame, using IPS might allow earlier lameness detection (and thus more effective treatment), especially if it can be done more frequently than LS. Previous studies of SLS and LS have been inconsistent, with some studies identifying more cows as lame using ≥2 indicators of SLS compared to LS [22], and others fewer [16,21]. Thus, the suggestion that IPS could be more sensitive than LS needs testing on more farms. Such research would also need to investigate the association between IPS and hoof lesions, especially in cows with a locomotion score of 1 and two IPS indicators.

This future research would also be an opportunity to address the findings of the DT process, in particular, to confirm that the DT presented in Figure 1 is the optimal tree and to identify whether combining multiple results from multiple IPS events would improve sensitivity. In addition, the value of combining such results in a machine learning process with other indicators, such as behaviour, milk production and live weight, that have been associated with lameness [47] should be evaluated.

5. Conclusions

The current study has shown that IPS accurately predicts LS. Using the DT machine learning procedure, we showed that IPS indicators were able to discriminate between cows with different locomotion scores. While using specificity/sensitivity analysis, we found that using a threshold of at least two positive indicators, IPS had a high specificity and sensitivity for detecting clinically lame cows (locomotion scores $\geq$ 2 on a scale of 0 to 3). Thus, our results suggest that the IPS technique has significant potential to be used as an alternative for detecting lameness in pasture-based dairy herds. However, this was a small study on a convenience sample of only two farms, so further research is required before IPS could replace LS. This investigation should focus on:

(1) Establishing the relationship between IPS and LS across more farms with different milking parlours and different prevalence of lameness and across more observers.
(2) Identifying whether the IPS procedure can be improved further to address issues with time for scoring (increasing the proportion of cows that can be scored per milking) and visibility of indicators.
(3) Determining whether IPS can reliably differentiate cows with locomotion score 1, which should only be monitored, from cows with locomotion score $\geq$2, which need examination and treatment.

Author Contributions: C.W.W. and the supervisory team conceptualised the study. First, C.W.W. collected data and did exploration, followed by conventional data analysis. Next, R.A.L. validated data analysis, and R.A.L. and D.A.Y. did a decision tree analysis using machine learning programming. Finally, C.W.W. wrote the first draft of the paper, which was contributed to and finally approved by all authors. L.J.L., K.R.M. and R.A.L. supervised the project. R.A.L. was responsible for funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The observations described in this study do not meet the definition for a manipulation in the New Zealand Animal Welfare Act 1999. Therefore, ethical approval for animal manipulations was not required.

Informed Consent Statement: The farmers were clients of the Massey Farm Practice and were interested in participating when informed about this project.

Data Availability Statement: Data are available at request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Sensitivity and specificity with 95% confidence interval for detecting lame cows (locomotion score ≥2) the number of observations on farm 1 (*n* = 3006), and on farm 2 (*n* = 1119).

IPS Indicators Present	Sensitivity	Specificity	PPV	NPV
SW	46.2 (35.8–56.9)	93.4 (92.5–94.3)	18.4 (14.8–22.6)	98.2 (97.8–98.5)
AWD	44.1 (33.8–54.8)	92.6 (91.6–93.5)	16.0 (12.7–19.8)	98.1 (97.7–98.4)
SHH	76.3 (66.4–84.5)	97.5 (96.8–98.0)	49.0 (42.7–55.2)	99.2 (98.9–99.5)
OH	38.7 (28.8–49.4)	87.0 (85.7–88.2)	8.7 (6.7–11.1)	97.8 (97.4–98.1)
One or more (≥1)	100.0 (96.1–100.0)	71.8 (70.1–73.4)	10.2 (9.7–10.7)	100.0
Two or more (≥2)	92.5 (85.1–96.9)	98.6 (98.1–99.0)	68.3 (61.1–74.6)	99.8 (99.5–99.9)
Three (3)	11.8 (6.1–20.2)	100.0 (99.9–100.0)	100.0	97.3 (97.1–97.5)
SW	32.5 (18.6–49.1)	95.0 (93.5–96.2)	19.4 (12.6–28.8)	97.4 (96.8–97.9)
AWD	55.0 (38.5–70.7)	93.2 (91.6–94.7)	23.2 (17.4–30.1)	98.2 (97.5–98.7)
SHH	77.5 (61.6–89.2)	96.3 (95.0–97.3)	43.7 (35.4–52.3)	99.1 (98.5–99.5)
OH	52.5 (36.1–68.5)	80.0 (77.5–82.3)	8.9 (6.6–11.8)	97.9 (97.0–98.4)
One or more (≥1)	100.0 (91.2–100.0)	66.1 (63.2–68.9)	9.9 (9.1–10.6)	100.0
Two or more (≥2)	95.0 (83.1–99.4)	98.4 (97.5–99.1)	69.1 (58.1–78.3)	99.8 (99.3–99.9)
Three (3)	22.5 (10.8–38.5)	100.0 (99.7–100.0)	100.0	97.2 (96.7–97.6)

SW = shifting weight, AWD = abnormal weight distribution, SHH = swollen heel or hock joint, OH = overgrown hoof, LS = locomotion score, PPV = positive predictive value, NPV = negative predictive value, Total-denotes the number of observed indicators.

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Chapter Five: Assessing Alternatives to Locomotion Scoring for Detecting Lameness in Dairy Cattle in Tanzania: Infrared Thermography

Foreword: This chapter covers the study that evaluated infrared thermography against locomotion scoring for lameness detection in dairy cows under combined (housing and grazing) production systems in Tanzania. Data were collected from three dairy farms with a milking herd of >50 cows in Morogoro. Cows were observed at two consecutive afternoon milkings. Locomotion scoring was undertaken at the first milking, and thermal imaging of the hind feet at the second milking. Mean foot skin temperature measured from the plantar aspect of hind limbs at a cut-off point of 38.0◦C revealed a sensitivity of 73.2% and a specificity of 86.0% for identifying cows with increased locomotion score (locomotion ≥2 (lame)). The manuscript has been submitted for publication in Tropical Animal Health and Production Journal. In this thesis, the article has been presented according to the journal format and style.

Assessing Alternatives to Locomotion Scoring for Detecting Lameness in Dairy Cattle in Tanzania: Infrared Thermography

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Abstract

Lameness detection is a significant challenge. Locomotion scoring (LS), the most widely used system for detecting lameness, has several limitations, including its subjective nature and the existence of multiple systems, each with its own advantages and disadvantages. Therefore, this study aimed to evaluate whether foot skin temperature (FST) of hind limbs, as measured using infrared thermography (IRT), could potentially be used as an alternative on Tanzanian dairy farms. Each of the three study farms were visited twice during the afternoon milking on consecutive days. DairyNZ LS (4-point scale (0–3) was undertaken on the first day as the cows exited the milking parlour after being milked, while on the following day, the plantar aspect of the hind limbs of the cows was thermally imaged while they were standing in the milking parlour, using a handheld T650sc forward-looking infrared camera. Mean FST was higher for cows with a locomotion score of 1 than those with a score of 0, higher for cows with a locomotion score of 2 than those with a score of 1, and higher for cows with a locomotion score of 3 than those with a score of 2, with each one-unit locomotion score increase being associated with a 0.57°C increase in mean temperature across all zones. The optimal cut-off point of 38.0°C for mean temperature across all zones was identified using a receiver operator characteristic curve. This cut-off point had a sensitivity of 73.2% and a specificity of 86.0% for distinguishing cows with a locomotion score ≥ 2 (clinical lameness). The prevalence of

clinical lameness across all three farms was 33%, which meant that only 72% of cows with a mean FST across all zones ≥38.0°C had been identified as clinically lame using LS. This study confirmed that IRT has the potential to be used to detect lameness on Tanzanian dairy farms. However, before it can be widely used, improvements in accuracy, especially specificity, are needed, as are reductions in equipment (IR camera) costs.

Keywords: lameness, locomotion scoring, infrared thermography, dairy cattle, tropical

5.0 Introduction

Early lameness detection accompanied by effective treatment is crucial to minimise the pain and discomfort associated with lameness (Ghotoorlar et al., 2012; Leach et al., 2012; Pedersen and Wilson, 2021) as well as decrease the risk of irreversible claw damage (Newsome et al., 2016).

Visual locomotion scoring (LS) is the most commonly used active lameness detection method on dairy farms (Schlageter-Tello et al., 2014). A wide range of different systems have been used; Schlageter-Tello et al. (2014) identified 25 different LS systems that had been published in the peer-reviewed literature. Across all systems, the most critical challenge of LS systems is their subjective nature, with both within- and between-observer variation being high, especially when training is limited (Ramanoon et al., 2018; Schlageter-Tello et al., 2015; Van Nuffel et al., 2015). Thus, training is particularly important when farmers and farm staff are undertaking lameness detection using LS.

An objective technique for identifying lame cows would thus be useful for on-farm detection of lameness, especially where farm staff training is difficult to achieve (e.g. because of lack of infrastructure or due to limited farmer knowledge). This is the situation in Tanzania, where active lameness detection using LS is extremely rare. In Tanzania, farm size is generally small and infrastructure limited, making training at the farm level expensive and challenging.

One potential alternative to visual LS is infrared thermography (IRT), a non-invasive technique that records body surface temperature and produces a pictographic representation of the scanned anatomical area (Eddy et al., 2001). Body extremities and surface temperature mainly depend on blood perfusion and tissue metabolism (Berry et al., 2003). Thus, changes in blood flow can influence the amount of radiated heat and thus be detected by IRT (Eddy et al., 2001). One reason for changes in tissue blood flow is the inflammatory response. Thus IRT has the potential to detect systemic infectious lameness such as foot-and mouth-disease (Rainwater-Lovett et al., 2009) and localised infectious lameness such as bovine digital dermatitis (Alsaaod et al., 2014) as well as non-infectious claw horn disease (Alsaaod and Büscher, 2012).

However, hoof temperature can be affected by factors other than foot diseases, such as physiological status (Nikkhah et al., 2005), environmental factors (Main et al., 2012; Wang et al., 2021), and activity level (Gloster et al., 2011). Thus the production system and management of the cows in a herd can significantly affect hoof temperature, potentially altering the accuracy of IRT as a means of lameness detection. Thus to determine the usefulness of IRT in a system, IRT needs to be tested in that system (Werema et al., 2021). Unfortunately, no data are available for tropical pastoral systems such as those which are common in many regions of Tanzania. Therefore, the aim of this study was to investigate the association between foot skin temperature (FST) of hind limbs at afternoon milking and locomotion scoring on three Tanzanian dairy farms where cows grazed tropical pasture between morning and afternoon milking.

5.1 Materials and Methods

5.1.1 Study Area and Animals

This study was undertaken in the Morogoro region of eastern Tanzania. This region has a sub-humid tropical climate with two wet seasons per year (long rains from March to June and short rains from October to December). Mean temperature ranges from 27 to 33.7°C and 14.2 to 21.7°C during the dry and wet seasons, respectively.

A convenient selection of three dairy farms was made for this study. All three herds had >50 cows, were milked twice daily, grazed natural pasture off-farm between morning and afternoon milking, and had a flat concrete surface outside the milking parlour, which was suitable for locomotion scoring. Calving was all year-round on the three study farms, and the herds were composed of mostly multiparous milking cows, as no regular replacement of cows was done on any of the farms. All three farms had only dairy breed cattle – a mixture of breeds and crossbreeds of European dairy cattle (Friesian, Ayrshire, Jersey, and their crossbreeds) and grazed their cattle on natural pastures (principally *Hyparrhenia* spp, *Megathyrsus maximus*, *Cenchrus ciliaris*, and *Brachiaria* spp) for approximately 8 hours after morning milking.

The distance between the grazing area and milking parlour on all farms was approximately 5 to 10 km with no constructed trackways. After the afternoon milking session, cows were allowed to graze around the farm before being taken to the free stall barns in the evening (6 pm), where they were given hay (principally, from *Chloris gayana* and *Pennisetum purpureum*) and homemade concentrates. All three farms had herringbone milking parlours. Farms 1 and 2 used milking machines (reverting to hand milking when there was no power), while farm 3 employed hand-milking only. During the study period, the milking herds had 52, 58, and 60 cows on farms 1, 2, and 3, respectively.

Routine hoof trimming and systematic locomotion scoring were not undertaken on any of the farms, and none of the farms had accurate lameness treatment records.

5.1.2 Study Visits

In March 2020, farms were visited during the afternoon milking on two consecutive days. Locomotion scoring was undertaken on the first day and on the second day, the plantar aspects of both hind feet of all cows were imaged using an infrared camera.

5.1.3 Locomotion Scoring

All locomotion scoring was undertaken by the first author (CWW) who was trained in the DairyNZ lameness score using a combination of video and supervised scoring of live animals (see Werema et al 2021 for further details). Prior to the study commencing in March 2020, CWW rewatched the training videos as a refresher.

On each farm, all milking cows were locomotion scored and their ear tag number recorded as they exited the milking parlour. The site chosen for scoring observations on each farm was a flat well-maintained concrete surface, that was at least 25 m long, and which was cleaned after every milking session. This area allowed the observer to view at a distance so as not to disturb cow flow and locomotion.

5.1.4 Infrared Thermography

During the afternoon milking following the LS, IRT imaging was performed using a handheld T650sc Forward-looking Infrared camera (FLIR Systems, Oregon, United States), with emissivity set at 0.95. Pictures were taken while the observer was standing at a distance of approximately 1 m from the cow, with the plantar aspects of both hind feet being imaged. Prior to imaging, no foot preparation was undertaken, except that cows walked through a footbath containing only water on entering the collecting yard for the milking parlour approximately 30 minutes before milking.

Foot images were analyzed using FLIR Tools software (FLIR Systems Oregon, United States) with estimates of the surface temperature obtained from seven zones on each hind foot as described by Werema et al. (2021) (see figure 5.1). The maximum temperature for each zone was used for analysis in line with previous infrared studies aimed at lameness detection in the cow (Stokes et al., 2012; Werema et al., 2021; Whay et al., 2004).

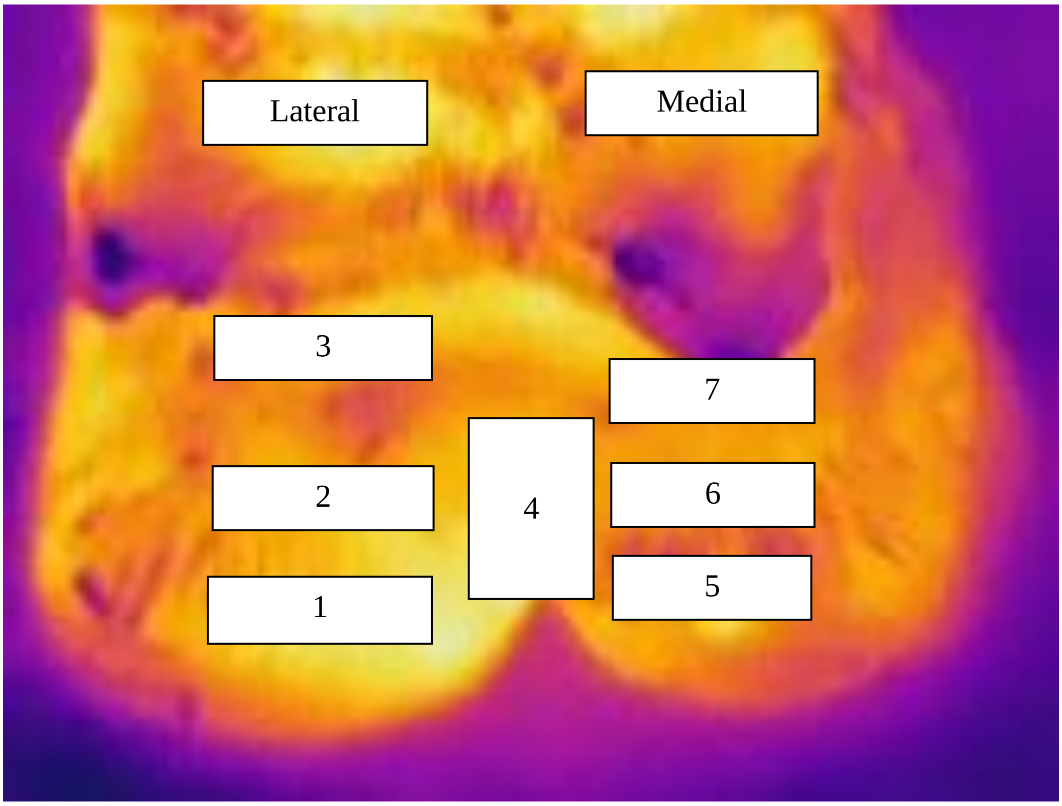

Figure 5.1: Infrared thermography image of the plantar aspect of the left hind foot overlaid to depict the seven zones for which estimates of surface skin temperature were measured. On the lateral claw; zone 1: coronary band (CB), zone 2: above the coronary band (ACB), zone 3: below accessory digit (BAD), zone 4: interdigital space (IDS). Zones 5 to 7 are the equivalent to zones 1 to 3 but on the medial claw.

5.1.5 Statistical Data Analyses

SPSS version 27 (IBM Corporation, Armonk, NY, USA) was used for all data analysis unless otherwise reported. Descriptive statistics were created for each zone temperature measure. The normality of foot temperature was visually assessed using Q-Q plots and histograms, followed by checking the skewness and kurtosis statistics. A generalised linear marginal repeated measures model was then used to evaluate the effect of the farm, foot, and zone within the foot on skin temperature. Farm and foot (right or left hind) were the independent variables, zone within foot the repeated variable and skin temperature the outcome variable. Interaction between farm and foot was tested and removed from the final model as it was non-significant (p>0.05). Covariance structure was identified using Quasi-likelihood under the independence model criterion (QIC). Residuals were checked for normality using Q-Q plots and histograms. Post-hoc pairwise comparisons between zones were undertaken using the Šidák correction for multiple comparisons (Abdi, 2007).

The association between locomotion score and foot temperature was tested using six temperature measures (see Table 5.1 for temperature definitions). Univariable analyses were first performed to assess the association between the outcome (foot temperature) and predictor (locomotion score) variables. This analysis identified significant heteroscedasticity when we compared foot temperature across locomotion scores. Therefore, we employed a generalised linear model with an identity link function and robust estimators (Astivia and Zumbo, 2019) to analyse the association between foot skin temperature and locomotion score. In model fitting, each temperature definition was used as the outcome variable, with farm and locomotion scores as the predictor variables. Two-way interactions between farm and locomotion scores were added, and backwards selection was then used to remove any interactions where p>0.05. Both main effects were kept in the final model irrespective of p-value.

Table 5.1: Definitions of the infrared thermography estimates utilised for analysis adopted from (Werema et al., 2021).

Foot/Zone *	**Description**
Mean temperature	Average temperature, across both feet (all 14 zones)
Hottest zone	Highest zone temperature, across both feet (all 14 zones)
Hottest zone 4	The highest zone 4 temperature on either foot
Hottest coronary band (CB)	The highest zone 1 or 5 temperature on either foot
Hottest above the coronary band zone (ACB)	The highest zone 2 or 6 temperature on either foot
Hottest zone below the accessory digit (BAD)	The highest zone 3 or 7 temperature on either foot

* For all analyses, the maximum temperature for each zone was used for the analysis.

Six receiver operator characteristic (ROC) curves were created, one for each temperature definition, with categorised locomotion score (lame (locomotion score ≥2) vs not lame (locomotion score <2)) to establish the sensitivity and specificity of IRT to predict locomotion score ≥2. Area under the curve (AUC) and coordinates of the curve (CC) were then used to evaluate a model's predictive accuracy. Optimal temperature cut-off values were identified by maximising sensitivity plus specificity. The statistical package MedCalc Version 19.5.1 (MedCalc Software, Ostend, Belgium) was then employed to calculate positive and negative predictive values for those optimal cut-off points.

5.2 Results

All milking cows were locomotion scored on all three farms. The distribution of locomotion scores is summarised in Table 2. Across the three farms, 33% of cows were identified as being lame (locomotion score ≥2).

Table 5.2: Distribution of locomotion score and their percentage in brackets on three farms in Morogoro, Tanzania

Farm name	Locomotion score				
	0	1	2	3	Total
1	11 (21.2)	24 (46.1)	12 (23.1)	5 (9.6)	52 (30.6)
2	15 (25.9)	25 (43.1)	15 (25.9)	3 (5.1)	58 (34.1)
3	13 (21.7)	26 (43.3)	14 (23.3)	7 (1.7)	60 (35.3)
Total	39 (23.0)	75 (44.1)	41 (24.1)	15 (8.8)	170 (100.0)

5.2.1 Effect of Foot and Foot Zone on Skin Temperature

On average the FST of the left foot was higher than the right foot (37.510°C and 37.411°C, respectively). However, it is unlikely that this is biologically significant as mean difference was only 0.099°C (95% CI: 0.003–0.194). However, biologically significant differences between zones were identified. For example, the difference between the zone with the lowest mean temperature (zone 6) and the zone with the highest mean temperature (zone 4) was 1.57°C (95% CI: 1.392–1.748). Results for all zones and their comparisons are summarised in Tables 3 and 4, respectively. Mean temperatures were higher for zones on the lateral claw than their equivalent zones on the medial claw (see Table 3); these differences were 0.243°C, 0.284°C, and 0.163°C for zones 1 vs 5, 2 vs 6, and 3 vs 7, respectively.

Table 5.3: The mean temperature (degrees centigrade) and 95% confidence interval for zones 1–7 (see Table 1 for definitions) for both hindlimbs on three dairy farms in Morogoro (n = 170).

		95% Confidence Interval	
Zone	Mean	Lower	Upper
1	37.823	37.781	37.865
2	37.021	36.956	37.086
3	37.460	37.449	37.472
4	38.307	38.291	38.322
5	37.580	37.515	37.645
6	36.737	36.699	36.774
7	37.297	37.264	37.329

Note: zones 1-3 are on the lateral claw, and 5-7 are equivalents on the medial claw.

Table 5.4: Comparisons of mean foot skin temperature (degrees centigrade) and 95% confidence interval for zones 1–7 (see Table 1 for definitions) for both hindlimbs on three dairy farms in Morogoro (n = 170).

			95% Confidence Interval	
(I) Zone	(J) Zone	Mean Difference (I-J)	Lower Bound	Upper Bound
1	2	.802	.528	1.077
	3	.363	.088	.637
	5	.243	-.032	.518
	6	1.086	.812	1.361
	7	.526	.252	.801
2	6	.284	.009	.559
3	2	.440	.165	.715
	6	.724	.449	.999
	7	.164	-.111	.439
4	1	.484	.209	.758
	2	1.286	1.011	1.561
	3	.846	.571	1.121
	5	.726	.452	1.001
	6	1.570	1.295	1.845
	7	1.010	.735	1.285
5	2	.559	.285	.834
	3	.120	-.155	.395
	6	.844	.569	1.118
	7	.284	.009	.558
7	2	.276	.001	.551
	6	.560	.285	.835

5.2.2 Infrared Thermography versus Locomotion Scoring

The mean FST for different locomotion scores is summarised in Table 5.For all six FST measures (see Table 1 for definitions), the temperature was higher for cows with a locomotion score of 1 than those with a score of 0, higher for cows with a locomotion score of 2 than those with a score of 1, and higher for cows with a locomotion score of 3 than those with a score of 2. The comparisons of all six-foot skin temperature measures versus different locomotion scores are presented in Table 6. As an example, for mean temperature, the mean difference between cows with scores 0 and 1 was 0.91°C (95% CI: 0.498–1.313); between scores 1 and 2 cows, it was 0.83°C (95% CI: 0.431–1.232), and between scores 2 and 3 cows, it was 0.65°C (95% CI: 0.026–1.271).

Table 5.5: The mean temperature (degrees centigrade) from plantar aspects across both feet (all 14 zones) and 95% confidence interval for different locomotion scores (0 – 3) DairyNZ on three farms in Morogoro (n = 170).

		95% Confidence Interval	
Locomotion score	Mean	Lower	Upper
0	36.447	36.136	36.759
1	37.354	37.193	37.514
2	38.190	38.002	38.379
3	38.811	38.628	38.993

Table 5.6: Comparisons of mean foot skin temperature for different zones versus locomotion scores (0 – 3) DairyNZ on three dairy farms in Morogoro (n = 170).

				95% Confidence Interval	
Temperature measure	(I) LS	(J) LS	Mean Difference (I-J)	Lower Bound	Upper Bound
MT	1	0	.906	.498	1.313
	2	0	1.737	1.276	2.198
		1	.831	.431	1.232
	3	0	2.386	1.759	3.012
		1	1.480	.897	2.063
		2	.649	.026	1.271
Hottest zone	1	0	.832	.421	1.243
	2	0	1.561	1.096	2.027
		1	.730	.326	1.134
	3	0	2.264	1.631	2.896
		1	1.432	.843	2.021
		2	.702	.074	1.330
Hottest zone 4	1	0	.894	.441	1.347
	2	0	1.573	1.060	2.086
		1	.679	.233	1.124
	3	0	2.359	1.663	3.056
		1	1.465	.817	2.114
		2	.787	.094	1.479
Hottest CB	1	0	.811	.374	1.248
	2	0	1.597	1.102	2.092
		1	.786	.356	1.216
	3	0	2.327	1.654	2.999
		1	1.516	.890	2.142
		2	.730	.062	1.398
Hottest zone ACB	1	0	.821	.380	1.263
	2	0	1.684	1.184	2.185
		1	.863	.429	1.297
	3	0	2.257	1.578	2.937
		1	1.436	.804	2.068
		2	.573	-.102	1.248
Hottest zone BAD	1	0	.870	.466	1.274
	2	0	1.639	1.181	2.096
		1	.768	.371	1.166
	3	0	2.361	1.739	2.983
		1	1.491	.912	2.069
		2	.722	.105	1.340

MT = mean temperature, CB = coronary band, ACB = above the coronary band, BAD = below the accessory digits.

5.2.3 Association of Foot Temperatures and Locomotion Scores

A linear association was demonstrated between individual cow locomotion scores and foot skin temperature for all six temperature measures. Detailed data are presented in Table 7. As an example, for mean temperature, each one-unit locomotion score increase was associated with a 0.57°C (95% CI: 0.46–0.70) rise in mean temperature.

Table 5.7: Temperature measures estimates and their 95% confidence intervals on three dairy farms in Morogoro (n = 170).

Model Parameter		95% Confidence Interval	
		Lower Bound	Upper Bound
Mean temperature (intercept)	38.662	38.394	38.930
Locomotion score *	0.565	0.457	0.699
Hottest zone (intercept)	40.057	39.807	40.307
Locomotion score *	0.568	0.459	0.702
Hottest zone 4 (intercept)	39.814	39.558	40.070
Locomotion score *	0.703	0.568	0.870
Hottest coronary band (intercept)	39.465	39.182	39.749
Locomotion score *	0.657	0.531	0.812
Hottest zone ACB (intercept)	38.471	38.182	38.760
Locomotion score *	0.671	0.542	0.829
Hottest zone BAD (intercept)	39.133	38.896	39.370
Locomotion score *	0.563	0.455	0.696

* Effect of increased locomotion score of 1 unit in DairyNZ lameness score. See Table 1 for the definition of temperature measurement. ACB = above the coronary band, BAD = below the accessory digits.

5.2.4 A Receiver Operating Characteristic (ROC) Analysis

A receiver operating curve is illustrated in Figure 5.2. Optimal threshold values, area under the curve and calculated parameters for temperature measures are summarised in Table 8.

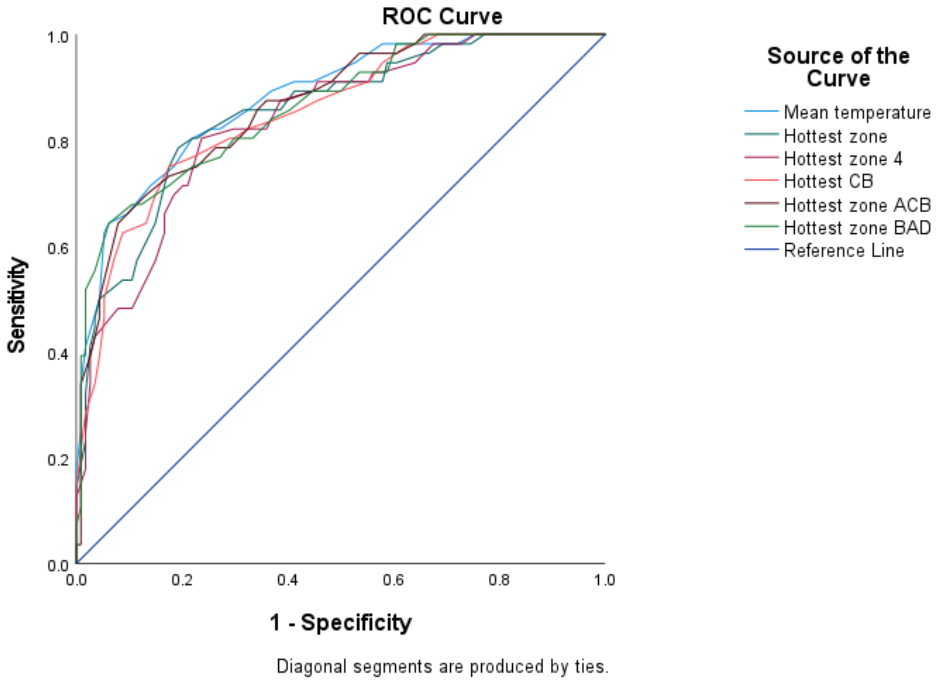

Figure 5.2: Receiver operating characteristic (ROC) curves were used to determine the optimal threshold values for the infrared thermography's sensitivity and specificity, assuming locomotion scores ≥2 as locomotion score = 2 on three dairy farms in Morogoro (n = 170). Note: coronary band (CB), above the coronary band (ACB), below accessory digit (BAD).

Table 5.8: Optimal cut-off points for skin foot temperature measurements (degrees centigrade) for determining lame cows (Dairy NZ lameness score ≥ 2) on three dairy farms in Morogoro (n = 170).

Temperature Measure [1]	**Optimal Threshold (°C)**	**AUC (95% CI)**	**Specificity (95% CI)**	**Sensitivity (95% CI)**	**PPV (95% CI) ***	**NPV (95% CI) ***
Mean temperature	38.0	0.88 (0.83–0.93)	86.0 (78.2-91.8)	73.2 (59.7-84.2)	71.9 (61.3-80.6)	86.7 (80.8-91.0)
Hottest zone	39.0	0.85 (0.79-0.91)	80.7 (72.3-87.5)	78.6 (65.6-88.4)	66.7 (57.3-74.9)	88.5 (82.2-92.7)
Hottest zone 4	38.9	0.84 (0.78-0.90)	79.8 (71.3-86.8)	71.4 (57.8-82.7)	63.5 (53.8-72.2)	85.1 (78.8-89.7)
Hottest CB	38.6	0.85 (0.79–0.91)	82.5 (74.2-88.9)	75.0 (61.6-85.6)	67.7 (57.8-76.3)	87.0 (80.9-91.4)
Hottest zone ACB	38.1	0.87 (0.81-0.92)	86.8 (79.2-92.4)	69.6 (55.9-81.2)	72.2 (61.1-81.1)	85.3 (79.6-89.7)
Hottest zone BAD	38.7	0.86 (0.80-0.92)	93.9 (87.8-97.5)	64.3 (50.4-76.6)	83.7 (71.0-91.5)	84.3 (79.0-88.4)

[1] See Table 1 for the definition of temperature measure; AUC, area under the curve; CI, confidence interval; PPV, positive predictive value and NPV, negative predictive value; CB, coronary band; ACB, above the coronary band; BAD, below accessory digit (BAD). *, PPV and NPV calculated at a prevalence of lameness of 32.94%.

5.3 Discussion

The objective of the current study was to assess the usefulness of infrared thermography (IRT) as a tool for detecting lameness in dairy cattle partly grazed and housed in a tropical region (Tanzania) versus visual locomotion scoring (LS).

5.3.1 Suitability of IRT for Measuring Foot Skin Temperature during Milking

On all three farms, unlike in New Zealand (Werema et al., 2021), there was sufficient time during milking to collect thermal images from all cows. Hand milking increased the time available for image collection as it was slower than when the machine was used, but during hand milking, the milker obstructed the cow's feet, and the cows were more restless, leading to frequent changes in foot posture. Thus, during hand milking, images were collected prior to a cow being milked.

One limitation of this study is that only hind feet were imaged as cows were photographed during milking. Not all lameness is hind-feet related; although data from housed cows suggest that hind limb lameness accounts for >90% of cases (Murray et al., 1996), in pasture-based dairy cattle in New Zealand, only 67% of lameness was in the hind limb (Chesterton et al., 2008). No such data are available from Tanzanian dairy cattle. However, it is likely that only recording FST of hind limbs lowered the sensitivity of IRT for lameness detection in these cattle. Further research is required to identify how much the sensitivity was lowered.

Another potential issue with IRT under Tanzanian conditions is the imaging of dirty feet. Prior to milking on all three farms, the cows were walked through a footbath containing water. This was routine practice on all three farms and was undertaken with the intention of reducing dirt on feet, although it is unlikely that there was any impact on foot cleanliness (Fjeldaas et al., 2014). As this study was undertaken in the dry season, the feet of all cows were generally clean and thus were not washed prior to IRT. In the rainy season, the accumulation of mud on the feet during grazing might influence the accuracy of IRT, especially if the feet are not cleaned before imaging. However, Stokes et al. (2012) reported that in the UK, maximum sensitivity plus specificity of IRT was achieved in feet that were not cleaned. Further longitudinal research is required to investigate whether this is also the case in Tanzania.

5.3.2 Effect of Claw and Zone on Skin Foot Temperature

In these cattle, the lateral claw had a higher mean temperature than the medial claw, with the highest difference of 0.28°C being between zones 2 and 6 (see Table 3). This difference is somewhat larger than the difference of 0.1°C we found under New Zealand conditions using the same camera and protocol for IRT (Werema et al., 2021), but it is smaller than the differences of 1.0 to 1.7°C that have been reported in studies in housed cows (Nikkhah et al., 2005; Wilhelm et al., 2015). The reason for this difference is unclear but may be related to different protocols and different equipment.

The effect of the claw was consistent across zones, with the mean temperature for zones on the lateral claw being higher than their equivalents on the medial claw (see Table 3). Additionally, the order was consistent across claws, such as if on the lateral claw, zone 1 had a higher mean temperature than zone 2, the same applied to zones 5 and 6 on the medial claw. However, the order was not the same as that reported by Werema et al. (2021). In the current study, zones 1 and 5 (coronary band) had a higher mean temperature than zones 3 and 7 (below accessory digit), whereas Werema et al. (2021) reported that zones 3 and 7 had a higher temperature than zones 1 and 5. The reason for this difference is unclear. It may be related to differences in hindlimb disease (e.g. increased infectious lameness in Tanzanian cattle). However, as we did not record hoof or limb lesions in either study, this has to remain a suggestion.

5.3.3 Infrared Thermography as a Predictor of Locomotion Score

In this study, mean foot skin temperature increased as locomotion scores increased (Table 5), consistent with previous studies of IRT and locomotion scores that used different protocols and devices (Lin et al., 2018; Rodríguez et al., 2016; Werema et al., 2021). Consistent with Werema et al. (2021), the current study found that each of the locomotion scores (0, 1 and ≥2) had significantly different mean FST. The key difference between our two studies in regard to FST and locomotion score was that in Tanzanian cattle, the optimal cut-off point was 38.0°C, whereas, in New Zealand, our optimal cut-off was 34.5°C (Werema et al., 2021). However, both these cut-offs are both much higher than the cut-offs used in studies in housed cattle in the Northern Hemisphere, e.g. 23.3°C (Lin et al., 2018), 25.25°C (Main et al., 2012), 25.5°C, (Rodríguez et al., 2016), and 27.0°C (Stokes et al., 2012). The reason for the large difference in optimal cut-off between our studies and those previous studies is unclear. However, it may be related to protocol differences (e.g. measuring different sites, using different equipment or cleaning feet before imaging), differences in the environment such as ambient temperature, and differences in cause of lameness (e.g. infectious vs non-infectious lameness). Further data on the factors driving these differences in the optimal cut-off points are required. However, our data suggest that optimal cut-offs are likely to be protocol and production system specific. Thus, cut-offs should not be transferred from one study in one system to another, even if similar protocols are used.

The specificity and sensitivity of IRT at our 38.0°C cut-off point for identifying cows with a locomotion score of ≥2 were both moderate (86.0 and 73.2%, respectively) and lower than the specificity and sensitivity we reported in New Zealand of 92.4 and 80.0%, respectively (Werema et al., 2021). However, as with the difference between the two studies in relation to optimal cut-off, the difference between our two studies is much less than the differences between previous studies, which have reported the specificity and sensitivity of IRT. For example, Lin et al. (2018) reported a sensitivity of 78.5% and specificity of 39.2%, while the equivalent figures for Rodríguez et al. (2016) were 46.7% and 89.7%, respectively, and for Stokes et al. (2012), they were 80% and 73%, respectively. As with optimal cut-off, we need more data on the factors which are driving this variability in specificity and sensitivity, but the much smaller differences between our two studies suggest that differences in protocols may be driving much of the difference between studies.

For alternative methods of lameness detection, it is the specificity that is the most important. If a technique is easy to apply, then moderate sensitivity can be overcome by repeated measurement. However, even relatively high specificity (>90%) can result in farmer fatigue if a high proportion of identified cows are not actually lame (O'Leary et al., 2020). This fatigue is determined by the positive predictive value (PPV), the proportion of the positive tests which are true positive. The PPV is determined by specificity and prevalence; thus, although the specificity was lower in our Tanzanian study than in New Zealand, the much higher lameness prevalence (33 vs 14%) meant that PPV was higher in the Tanzanian study.

Nevertheless, a PPV of 72% at the optimal cut-off of 38.0°C is not ideal as ~1/4 of the cattle identified will not have changes in gait and posture associated with clinical lameness. However, such issues may be tolerated in the small dairy herds in Tanzania, where the number of false positive cattle identified at any one time may be relatively small. Further research is required to better understand Tanzanian dairy farmers' approach to lameness and whether this technological approach is likely to be acceptable on Tanzanian dairy farms.

One fundamental limitation of the current study is equipment cost. The FLIR camera is not likely to be affordable for most farmers, especially in lower-middle-income countries like Tanzania. However, the costs of infrared cameras are decreasing, and the development of smartphone apps which utilise IRT technology may make the technology affordable even for

Tanzanian farmers. Thus, our data suggest that if these changes continue, IRT may, in the future, be a useful objective method of detecting lameness in Tanzanian dairy cows.

5.4 Conclusion

The current study showed that, with a trained observer, locomotion scoring after milking can be a useful method of lameness detection under Tanzania conditions. However, the study farms were chosen based on having a suitable area for observation, so may not be typical of Tanzanian dairy farms. Further evaluation of LS on Tanzanian dairy farms is warranted, but the requirement for a trained observed may remain a key issue. The present study results demonstrated that FST measured by IRT was able to differentiate between cows with different locomotion scores. However, the sensitivity and, especially, the specificity of IRT need to be improved before it can be recommended for lameness detection under Tanzanian conditions. Additionally, the development of cheap, accurate smartphone IRT apps is needed for such technology to become affordable even on large Tanzanian dairy farms.

Author Contributions: C.W.W. and the supervisory team conceptualised the research. C.W.W. collected data and did data analysis. R.A.L. validated data analysis. C.W.W. wrote the first draft of the manuscript, which was contributed to and approved by all authors. L.J.L., K.R.M. and R.A.L. supervised the project. R.A.L. was responsible for funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Statement of Animal Rights: The observation and image capture described in this study does not meet the definition of manipulation in the Tanzania Animal Welfare Act 2008. Therefore, ethical approval for animal manipulations was not required.

Data Availability Statement: Data are available at request from the corresponding author.

Conflict of Interest Statement: The authors declare no conflict of interest.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

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Name of candidate:	Chacha Wambura Werema
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Chapter Six: Investigating the Effect of Prophylactic Claw Trimming on Lameness in Pasture-based Dairy Cows.

Foreword: This chapter covers the study that evaluated the impact of prophylactic hoof trimming for lameness prevention on a 940-cow spring-calving herd on the North Island of New Zealand. Two hundred fifty cows were selected randomly and trimmed at three different points of the production cycle (i.e. at drying-off, early lactation, and end of lactation). After calving, cows were locomotion scored fortnightly until the end of the lactation. The study revealed that a regime of three preventative trims did not decrease lameness prevalence or time to clinical lameness (LS 2). The manuscript has been submitted for publication in New Zealand Veterinary Journal. In this thesis, the manuscript has been presented in journal format and style.

Investigating the Effect of Prophylactic Claw Trimming on Lameness in Pasture-based Dairy Cows.

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Abstract

Aims: To evaluate in a pasture-based dairy herd the response to a three timepoint regime of hoof trimming (prior to dry-off, early lactation, and end of lactation) on lameness incidence and on time from calving to an elevation of locomotion score (LS).

Methods: This study was conducted on a 940-cow spring-calving herd on the North Island of New Zealand between May 2018 and May 2019. Two hundred and 50 cows were randomly allocated to the hoof trimming group, with the remainder assigned to the non-trim cohort. One trained professional hoof trimmer used the five-step Dutch method to trim the hind feet of the hoof trimming group. Throughout the subsequent production season, the whole herd was locomotion scored fortnightly using the 4-point (0-3) scale Dairy NZ lameness score. Kaplan-Meier survival curves were used to assess the univariable effect of hoof trimming on the interval between calving and first LS of ≥2 and first LS≥1. A multivariable Cox proportional hazards regression was then used to evaluate further the effect of claw trimming on time to elevated LS.

Results: Mean lameness prevalence (LS≥2) was 2.6%, with 30% of cows with four or more LS observations during the study period having at least one LS≥2. For LS≥1, the mean prevalence was 40%, with 98.6% of cows with four or more LS observations during the study period having at least one LS≥1 during lactation. Hoof trimming had no apparent effect on the incidence of LS≥2, but it did influence LS≥1. The hazard of a cow having a first LS≥2 in the control group was 0.87 (95% CI: 0.66 – 1.14) times that of the trimmed group; however, the hazard of a cow having a first LS≥1 was 1.60 (95% CI: 1.37 – 1.88) times higher in the control group than in the trimmed group.

Conclusion and clinical relevance: On this farm, prophylactic hoof trimming did not evidently influence lameness incidence or increase time to first LS≥2. This may have been because claw horn imbalance was not pronounced on this farm, with 53% of cows needing no trim on either hind limb on the first trimming occasion. Further research on the response to prophylactic trimming in pasture-based dairy cattle is required, which should focus on identifying the factors affecting the response to trimming in such cattle.

Keywords: lameness; locomotion scoring; hoof trimming; dairy cows; pasture-based

6.0 Introduction

Lameness causes significant economic losses and welfare problems in dairy cattle worldwide. Multiple studies have reported impacts of lameness on milk production, fertility, and on-farm longevity (Archer *et al.* 2010; Machado *et al.* 2010; Somers *et al.* 2015), as well as significant impacts on animal welfare (Laven and Holmes 2008; Whay and Shearer 2017).

Lameness aetiologies can be divided into infectious and non-infectious (Potterton *et al.* 2012). Both are important (Potterton *et al.* 2012), but whereas infectious causes, especially digital dermatitis, can be controlled by effective biosecurity and improvements in farm hygiene (Laven and Hunt 2002; Speijers *et al.* 2010; Solano *et al.* 2017), non-infectious lameness (which is principally caused by claw horn disruption lesions (CHDL)) are much more difficult to control. Claw horn diseases are thus considered to be the main challenge to reducing lameness in dairy cattle (Murray *et al.* 1996; Potterton *et al.* 2012; Shearer *et al.* 2015).

CHDL accounts for approximately 65% of lameness cases in housed cows (Murray *et al.* 1996; Bicalho and Oikonomou 2013). The numbers are similar in pasture-based systems. For example, in New Zealand, Chesterton *et al.* (2008) reported that CHDL accounted for 72.5% of diagnoses in lame cows treated by a veterinarian. CHDL are associated with pressure load within the foot (Van der Tol *et al.* 2004). The lateral claw is larger than its medial counterpart (Nacambo *et al.* 2007), and the lateral claw carries more weight (Van der Tol *et al.* 2002, 2003). This situation worsens when the lateral claw becomes overgrown (Van der Tol *et al.* 2004) and is exacerbated when weight shifts from one limb to another (Nuss *et al.* 2019). Therefore, one area of significant focus is maintaining normal claw conformation to reduce the pressure imbalance within the foot, i.e. decreasing CHDL through preventative functional claw trimming (Toussaint Raven 1985; Shearer and van Amstel 2001).

Multiple studies have shown that preventative claw trimming reduces the risk of lameness, prevents claw horn lesions, and improves performance in housed dairy cows (Manske *et al.* 2002; Fjeldaas *et al.* 2006; Hernandez *et al.* 2007; Van Hertem *et al.* 2014; Sadiq *et al.* 2021). However, a review by Stoddard and Cramer (2017) reported inconsistent benefits of prophylactic hoof trimming across different production systems. The evidence for the benefit of preventive trimming is more limited in cows at pasture than in housed cows. Sadiq *et al.* (2021) reported that claw trimming increased the time to first lameness in both permanently housed cows and in cows allowed to graze. However, the grazing cattle only had access to grazing for 3-6 hours per day and therefore were housed for the majority of their day. As far as the authors are aware, the only published study of preventative claw trimming and lameness in cows that are permanently kept at pasture is that by Bryan *et al.* (2012), who studied the effect of trimming on three dairy farms in Canterbury in the South Island of New Zealand. They reported no effect of claw trimming on subsequent lameness incidence, but they found that the median days to lameness was lower in the control group than in the trimmed group (29 versus 38 days; $p < 0.001$). In addition, they reported that HR for the control group becoming lame was 1.56 (95% CI 1.10–2.26; $p = 0.021$) times that of the treatment group. However, in that study, hoof trimming was undertaken in November in cows which had calved between July and October, so it may have been too late to produce an optimal effect.

There is thus a need for more research on the impact of trimming on the risk of lameness in cattle based permanently at pasture. The aim of the present study was, therefore, to evaluate the response to a three time point regime of claw trimming (prior to dry-off, early lactation, and end of lactation) on lameness incidence and time to first lameness case after calving in a pasture-based dairy herd in the North Island of New Zealand.

6.1 Materials and methods

6.1.1 Animals and farm location

The study was approved by Massey University Animal Ethics Committee (protocol number 8/22). The study was conducted on the 940 spring-calving cows on a dairy farm in the Manawatu-Wanganui region of New Zealand during the May 2018 to May 2019 production season. The majority of the cows were Friesian and Jersey crossbreds, with roughly 10% Friesian cows. Animal age ranged from 2 to 10 years (mean 4 years). The milking cows were managed as two groups that grazed separately. Both groups were then milked twice daily through a 60-unit rotary milking parlour.

Routine lame cow management included identification of lame cows during routine operations by farm staff, with veterinary visits to treat lame cows at least every two weeks (more frequently if required). Systematic locomotion scoring was not used by farm staff before or during the study. Once cows were identified as lame, they were put into a lame-cow group until the farmer determined they were no longer lame. This group was kept on a paddock (confined grazing area) close to the milking parlour and milked once a day in the morning. The farm was selected for the study on the basis of the farmer being interested in the study and the close working relationship with the veterinary practice, not on an identified lameness problem or a problem with claw conformation. The leading causes of lameness on the farm were white line disease, sole injury, and foot rot definitions as per (Chesterton *et al.* 2008). Digital dermatitis had not been diagnosed at any time prior to the study's start.

6.1.2 Visit 1: May 2018, Prior to Dry-off.

6.1.2.1 Allocation of Cows to Treatment Groups

The 940 spring calving cows were mixed on the feed pad (covered concrete area where cows were fed supplementary feed). The gate was then opened, and ~20 cows were let out from the feed pad onto the collecting yard and lined up for claw trimming. Once these cows had been trimmed, the remaining cows on the feed pad were mixed again, and the process repeated until 250 cows had been assigned to treatment (claw trimming). This process took place over three consecutive days, with trimming being undertaken for four hours per day. Finally, all the remaining cows (n = 690) were assigned to the non-trim cohort.

6.1.2.2 Protocol for Cows not Allocated to Trimming:

All non-trim animals except for 20 cows selected for a related study were released directly to pasture and managed according to farm protocol in their usual herd group with no further manipulations.

6.1.2.3 Protocol for Cows Allocated to Trimming:

Trim cows: Trimming was performed by a single trained professional hoof trimmer (with >25 years of experience) using a mobile hydraulic Wopa Pro+ Cattle Crush (VeeHof Dairy Services LTD, Canterbury, New Zealand) with accessories to restrain the cows. After trimming at visits 1, 2, and 3 cows were returned to their original groups. In this study, only hind limbs were appraised. The hoof trimmer (FH) assigned each hindfoot to one of four categories: **0,** trim not required; **1,** light trim required (trim to remove slight difference between the claw height); **2,** medium trim required (trim to correct marked claw height differential); **3,** heavy trim (therapeutic trimming for obvious lesion). The category was recorded alongside cow identification and the presence of any claw horn lesions directly into a Microsoft Excel spreadsheet. An angle grinder (a professional trimming disc) and Hauptner hoof trimming knives were then employed to trim the claws using the five-step Dutch method described by Toussaint Raven (1985). Briefly, this trimming procedure involves 1) trimming the toe length of the medial claw to 75 mm, leaving 5 to 7 mm thickness in the tip of the toe and sparing the height of the heel 2) making the lateral claw equal in length and weight-bearing surface to the medial (or as near as possible), 3) making a slope in the soles, 4) reducing the weight in the affected claw (if lesions present), and 5) removing loose horn and hard ridges.

6.1.3 Visit 2 (October 2018) Early Lactation and Visit 3 (May 2019) Prior to Dry-off

Cows in the trim group were separated from the main herd, restrained for a trim evaluation, and trimmed if necessary (recording as described for Visit 1). To assess differences in the trim category between feet and between trimming occasions, the trim category was recorded as an ordinal variable (0, 1, 2, and 3, such as no trim required, light trim required, medium trim required, and heavy trim required, respectively) at the level of the foot and the cow level. To evaluate the effect of prophylactic hoof trimming on the occurrence of lameness, a three timepoint trimming regime was followed by LS fortnightly throughout the production season.

6.1.4 Locomotion Scoring

Before the study began in May 2018, the first author, a veterinarian, was trained in locomotion scoring using the 4-point (0-3) scale Dairy NZ lameness score (Werema *et al.* 2021). The training consisted of observing training videos created by DairyNZ (DairyNZ) and Agriculture and Horticulture Development Board (AHDB), followed by supervised locomotion scoring on-farm (live cows) with a trained and experienced observer until the trainer was satisfied that the trainee could perform locomotion scoring effectively. Cows were locomotion scored as they exited the parlour after milking. Interobserver reliability between trainer and trainee was substantial (kappa =0.870; 95% CI:0.771 – 0.926).

The locomotion scoring area on the study farm was a flat concrete surface about 20 m in length. This walking distance was enough to assess cows' gait and posture attributes while exiting the milking parlour. Throughout the 2018/19 production season, the whole spring-calving herd, excluding the lame cow group, was locomotion scored fortnightly as they exited the milking parlour during the afternoon milking session. A list of all cows that scored ≥ 2 (lame cows) during a scoring session was provided to the farmer to allow them to be drafted for examination and treatment at the next routine lameness visit if the farmer so desired. In addition to this identification process, farm staff continued to observe the herd for lameness throughout the production season.

6.1.5 Statistical Analyses

All data were analysed using SPSS version 27 (IBM Corporation, Armonk, New York, United States of America). Descriptive statistics were created for the locomotion scores and claw trimming data sets. Multinomial logistic regression was used to establish the association of trimming categories assigned between feet per cow and trimming occasions. The Chi-squared test was employed to compare trim categories between feet within a cow and between trim occasions.

To evaluate the impact of claw trimming on the risk of lameness. Kaplan-Meier survival curve analysis was used to assess the univariable effect of claw trimming on both the interval between calving and first locomotion score of ≥2 and the interval between calving and first locomotion score ≥1, with a log-rank test being used to compare the distribution of the survival curves of the two treatment groups. If a cow was identified as lame by farm staff before it was observed as having an increased LS, its treatment date was recorded as the date when it had first had an elevated score, i.e. if all scores before lameness treatment were zero, a treated cow would be recorded as having their first score ≥1 and ≥2. However, if they had a score of 1 (but not a score of ≥2), they would be recorded as having only their first score ≥2. Any cows which did not record a score of ≥1 or ≥2 were censored at their last locomotion score. Only cows that calved between July and October 2018 and had at least four locomotion scores were included in this analysis.

A multivariable Cox proportional hazards regression was then used to evaluate further the effect of claw trimming on survival. Two models were fitted: the first had days from calving to first locomotion scores ≥2 (clinical lameness) as the dependent variable, and the second had calving to first locomotion score of ≥1 (imperfect gait). The trimming group, age, and breed were the predictor variables for both models. The breed was categorised as Friesian, Jersey, and Friesian x Jersey crossbred, while age was categorised as ≤ 4 years, 5 - 7 years, and ≥ 8 years.

6.2 Results

The age, breed and calving date of the two treatment groups are summarised in Table 6.1. Ten cows, with 5 in each trimming and the non-trim group, were excluded from the analysis as they had less than four locomotion scores throughout the study duration.

6.2.1 Locomotion Scores and Lameness Incidence

A total of 10 925 (3013 (27.6%) trim, 7912 (72.4%) non-trim) locomotion scores were recorded on 19 occasions between 15 August 2018 and 08 May 2019. Over this period, three locomotion scores of 3 (3 cows all non-trim) and 277 scores of 2 (239 cows; 68 (28.5%) trim, 171 (71.5%) non-trim) were recorded. The frequency distribution of locomotion scores during the study period is summarised in Table 6.2. Mean prevalence of locomotion scores ≥2 was 2.6% (0.82% trim, 1.74% non-trim).

Thirty-five cows were drafted by the farm staff for lameness treatment. Of those cows, 31 (88.6%) had been observed by the first author as having at least one locomotion score≥1 before treatment. Thus four cows drafted for treatment by the farm staff had not been observed as having an elevated LS prior to drafting. Of those treated cows, 17 (48.6%) had been observed as having at least one score ≥2, and 18 had not been observed as having an LS>1. Once cows treated for lameness were included, 11/ 807(1.4%) cows never had a score >0, 796 (98.6%) had at least one score of ≥1, and 242 (30%) had at least one score ≥2.

6.2.2 Claw trimming category

Two hundred fifty cows were trimmed during the first visit (dry-off), 221 cows during the second visit (early lactation), and 214 cows during the third trimming visit (end of lactation). The reason for the lower numbers was not specifically recorded, but in most cases, the cow was still present on the farm, so the principal reason was that the cows were simply not presented by the farmer. Table 6.3 summarises the trim category by foot and trimming occasion. Due to the low number of cows requiring a heavy trim, data for heavy trim and medium trim were combined for further analysis. The odds of being assigned a light trim rather than no trim was 1.5 (95% CI:1.15 – 1.81) times higher for the left than the right foot, while for a medium/heavy trim rather than no trim, the odds were 1.3 times higher (95% CI: 0.89 – 1.91). Trim occasion had no clear effect on the odds of having a light rather than no trim. Compared to the May 2019 trim, the odds ratios (OR) were 0.8 (95% CI: 0.61 – 1.06) for the May 2018 trim and 1.27 (95% CI: 0.96 – 1.69) for the October 2018 trim. In contrast, trim occasion was associated with a change in the odds of having a medium/heavy trim rather than no trim. Compared to the May 2019 trim, the OR were 0.34 (95% CI: 0.22 – 0.53) for the May 2018 trim and 0.35 (95% CI: 0.21 – 0.57) for the October 2018 trim. The effect of trim occasion and limb on trim category is illustrated in Table 6.4.

6.2.3 Claw Lesions Observed at Trimming

The claw lesions observed at trimming included overgrown hoof, sole haemorrhage, sole ulcer and white line disease. The most common lesion type was white line disease, observed in 7.4% of cows over all three trimming visits, followed by sole haemorrhage (6.3% of cows) (see Table 6.5).

6.2.4 Survival Analyses

In the non-trim group, 168/584 (28.8% 95% CI: 26.65 – 30.89) cows were recorded as having at least one LS≥2 versus 74/223 (33.2% 95% CI: 31.06 – 35.31) of the trimmed group. No clear difference was identified between treatment groups in the interval between calving and first locomotion score ≥2 ($p = 0.168$), with mean time to first LS≥2 being 233 (95% CI: 221.8 – 245.1) and 255 (95% CI: 247.5 – 262.2) days for trimmed and non-trimmed cows, respectively (see Figure 6.2).

For the interval between calving and first LS≥1, a clear difference was identified ($p < 0.001$), with median time to first LS≥1 being 57 (95% CI: 49.7 – 64.3) and 35 (95% CI: 32.0 – 38.0) days for trimmed and non-trimmed cows, respectively (see Figure 6.3).

The effect of the predictor variables on the hazard of LS≥1 and LS≥2 are summarised in Table 6.6. For LS≥2, only age had a clear association with hazard. After accounting for age and breed, the hazard of a cow having a first locomotion score ≥2 in the control group was 0.87 (95% CI: 0.66 – 1.14) times that of the trimmed group (see Figure 6.4). For LS≥1, neither breed nor age had a clear association with hazard. After accounting for breed and age, the hazard of a cow having a first locomotion score ≥1 was 1.60 (95% CI: 1.37 – 1.88) times higher in the control group than in the trimmed group (see Figure 6.5).

Table 6.1: Comparison of age, breed, and calving date between treatment groups (n = 807).

Age - number of cows (%)	**Non-trim**	**Trim**
≤4 years	342 (58.6)	109 (48.9)
5 - 7 years	206 (35.3)	103 (46.2)
≥8 years	36 (6.2)	11 (4.9)
Breed - number of cows (%)		
Friesian	50 (8.6)	16 (7.2)
Jersey	5 (0.8)	2 (0.9)
F x J	529 (90.6)	205 (91.9)
Calving date		
Mean (95% CI)	21/08/18 (20 – 23/08/18)	24/08/18 (22 – 26/08/18)
Median (Minimum - Maximum)	19/08/18 (04/07 – 13/10/18)	22/08/18 (13/07 – 12/10/18)

F = Friesian, J = Jersey, % = percentage, CI = confidence interval, Min = minimum, Max = maximum.

Table 6.2: Frequency distribution of locomotion scores for different farm visits during one production season (n = 10925).

Visit	LS0	LS1	LS≥2	TT	TNT	MT	MNT
1	152	82	3	44	193	206	497
2	240	101	10	95	256	155	434
3	306	172	9	127	360	123	330
4	354	175	13	156	386	94	304
5	368	192	16	160	416	90	274
6	304	232	15	159	392	91	298
7	360	252	15	167	460	83	230
8	333	208	9	151	399	99	291
9	285	194	16	154	341	96	349
10	372	311	16	192	507	58	183
11	312	260	17	165	424	85	266
12	369	294	13	176	500	74	190
13	409	291	15	194	521	56	169
14	349	257	18	180	444	70	246
15	478	211	18	200	507	50	183
16	467	240	17	203	521	47	169
17	358	228	20	167	439	83	251
18	355	193	22	151	419	99	271
19	347	234	18	172	427	78	263

LS = locomotion score; TT = total trim cows scored; TNT = total non-trim cows scored; MT = missed trim cows; MNT = missed non-trim cows.

Table 6.3: Claw trimming categories and limb assigned after claw trimming by trimming occasion.

Trimming	Left hind limb		Right hind limb	
category	Frequency	Percentage (%)	Frequency	Percentage (%)
1st Trimming				
No trim	120	48.0	143	57.2
Light trim	110	44.0	92	36.8
Medium trim	17	6.8	14	5.6
Heavy trim	3	1.2	1	0.4
Sub-total	**250**	**100.0**	**250**	**100.0**
2nd Trimming				
No trim	84	38.0	104	47.1
Light trim	126	57.0	102	46.1
Medium trim	11	5.0	15	6.8
Heavy trim	0	0.0	0	0.0
Sub-total	**221**	**100.0**	**221**	**100.0**
3rd Trimming				
No trim	83	38.8	99	46.3
Light trim	93	43.4	81	37.8
Medium trim	38	17.8	31	14.5
Heavy trim	0	0.0	3	1.4
Sub-total	**214**	**100.0**	**214**	**100.0**
Overall				
No trim	287	42.0	346	50.5
Light trim	329	48.0	275	40.1
Medium trim	66	9.6	60	8.8
Heavy trim	3	0.4	4	0.6
Grand-total	**685**	**100.0**	**685**	**100.0**

The first claw trimming was conducted during dry-off (May/June 2018), the second trimming was undertaken in early lactation (October 2018), and the third trimming was performed at the end of the lactation (May 2019).

Table 6.4: Comparison between trim category on the right hind foot with trimming category on the left hind foot of the same cow.

			HRF			
Date			0	1	2	Total
28-MAY-18	HLF	0	107	13	0	120
		1	33	73	3	109
		2	3	6	8	17
	Total		**143**	**92**	**11**	**246**
02-OCT-18	HLF	0	76	8	0	84
		1	28	93	5	126
		2	0	1	10	11
	Total		**104**	**102**	**15**	**221**
10-MAY-19	HLF	0	68	15	0	83
		1	29	58	6	93
		2	2	8	25	35
	Total		**99**	**81**	**31**	**211**
Total	HLF	0	251	36	0	287
		1	90	224	15	329
		2	5	15	42	69
	Total		**346**	**275**	**57**	**668**

HLF = hind left foot, HRF = hind right foot, 0 = no trim, 1 = light trim, and 2 = medium trim. The number of heavy trims were 4, 0, and 3 on the first, second and third trim occasions, respectively.

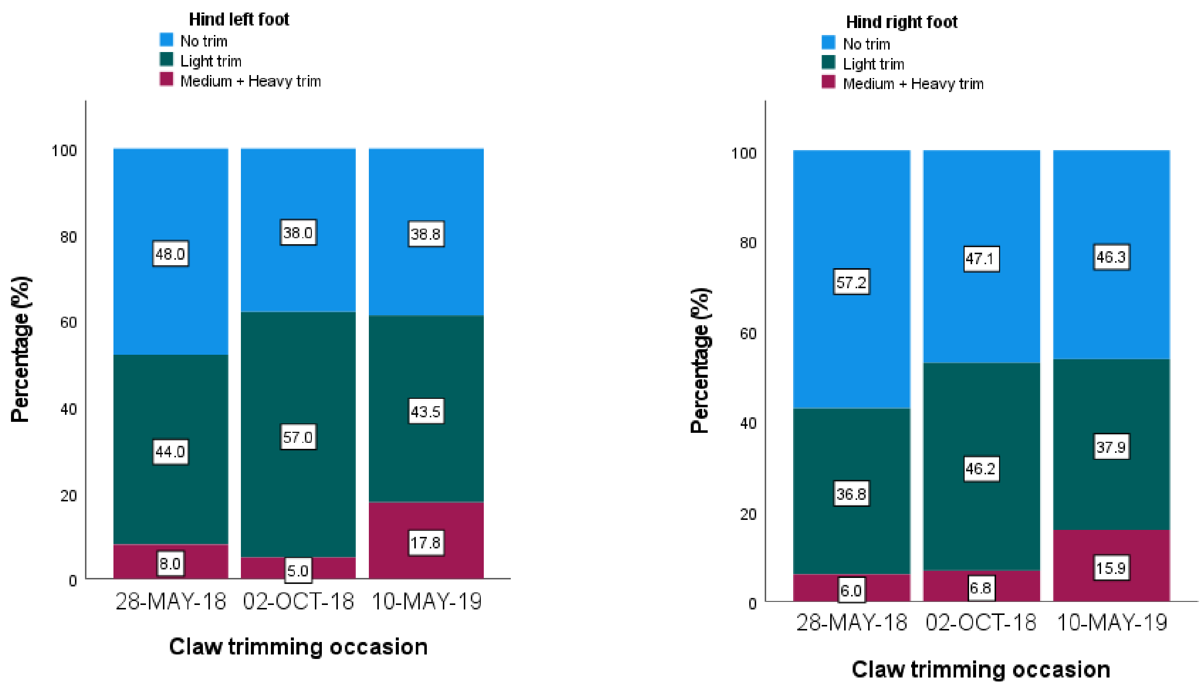

Figure 6.1: The distribution of left and right hind limb claw trimming category for three trimming occasions.

Table 6.5: Claw lesions observed after claw trimming by trimming occasion.

Lesion type	Number of cows	Percentage (%) of cows
1st Trimming		
None	212	84.8
Overgrown hoof	7	2.8
Sole haemorrhage	8	3.2
Sole ulcer	2	0.8
White line disease	21	8.4
2nd Trimming		
None	171	77.4
Overgrown hoof	2	0.9
Sole haemorrhage	25	11.3
Sole ulcer	0	0.0
White line disease	23	10.4
3rd Trimming		
None	193	90.2
Overgrown hoof	4	1.8
Sole haemorrhage	10	4.7
Sole ulcer	0	0.0
White line disease	7	3.3
Overall		
None	576	84.1
Overgrown hoof	13	1.9
Sole haemorrhage	43	6.3
Sole ulcer	2	0.3
White line disease	51	7.4
Total	**685**	**100.0**

The first claw trimming was conducted during dry-off (May/June 2018), the second trimming was undertaken in early lactation (October 2018), and the third trimming was performed at the end of the lactation (May 2019).

Table 6.6: The coefficients of the predictor variables on the hazard of LS≥2 and LS≥1 (from Cox proportional hazards model).

LS category	Model coefficient	p-value	HR	95% CI	
For LS≥2					
Non-trim group	-0.141	0.317	0.87	0.66	1.14
Breed (cat=1)	0.261	0.227	1.30	0.85	1.98
Breed (cat=2)	-0.129	0.856	0.88	0.22	3.54
Age (cat=1)	-0.577	0.023	0.56	0.34	0.92
Age (cat=2)	-0.110	0.666	0.90	0.54	1.48
For LS≥1					
Non-trim group	0.471	0.001	1.60	1.37	1.88
Breed (cat=1)	-0.106	0.412	0.90	0.70	1.16
Breed (cat=2)	-0.580	0.159	0.56	0.25	1.26
Age (cat=1)	-0.115	0.461	0.89	0.66	1.21
Age (cat=2)	-0.137	0.389	0.87	0.64	1.19

LS = locomotion score, cat = category, CI = confidence interval, HR = hazard ratio. Breed: Friesian (reference category 0), Jersey (cat 1), and Friesian x Jersey crossbred (cate2); age ≤4 years (reference category 0), 5 - 7 years (cat 1), and ≥8 years (cat 2).

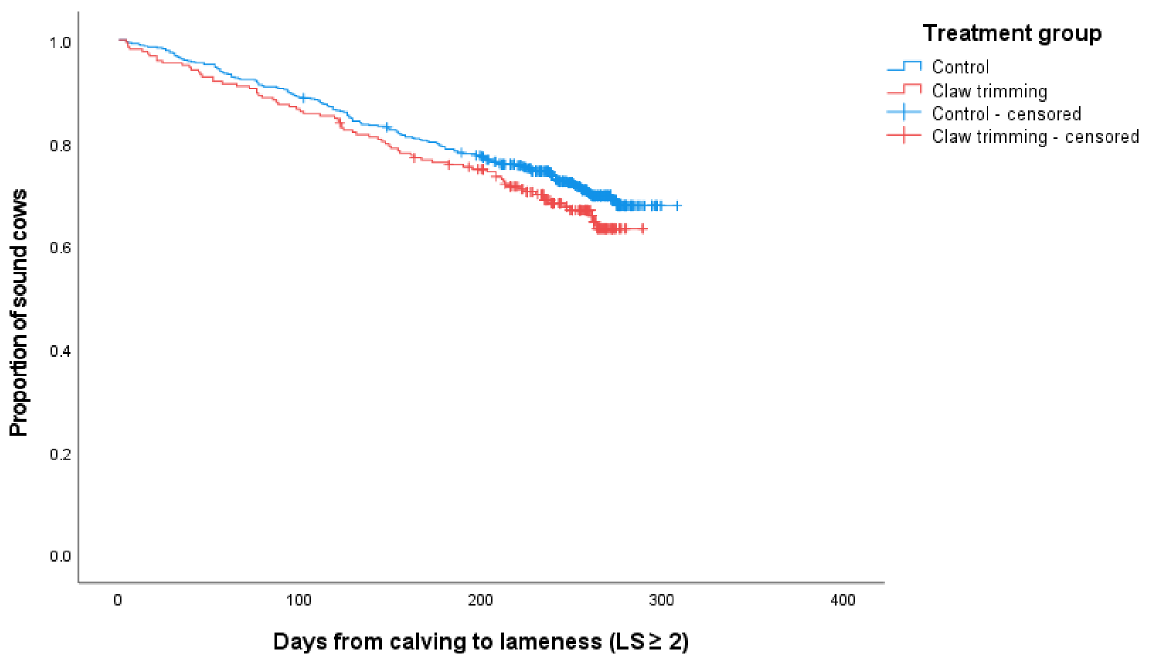

Figure 6.2: Kaplan Meier survival curves of the time from calving to lameness (LS ≥2) on one dairy farm for the 2018/2019 lactation season (n = 807).

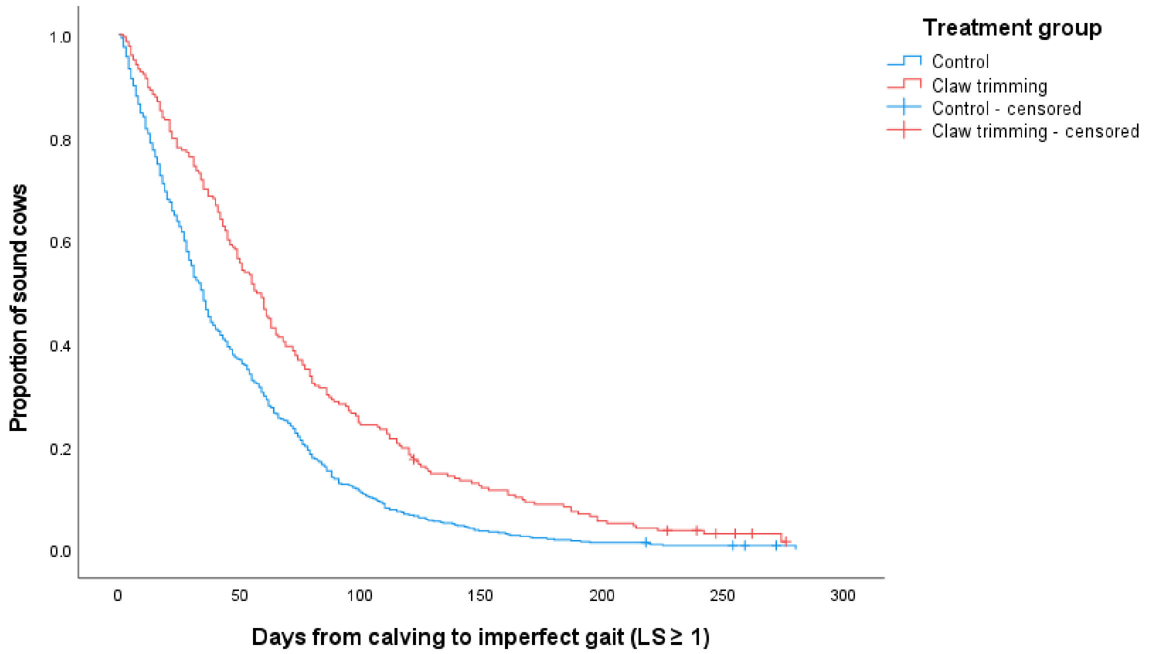

Figure 6.3: Kaplan Meier survival curves of the proportion of the time from calving to imperfect gait (LS ≥1) on one dairy farm for the 2018/2019 lactation season (n = 807).

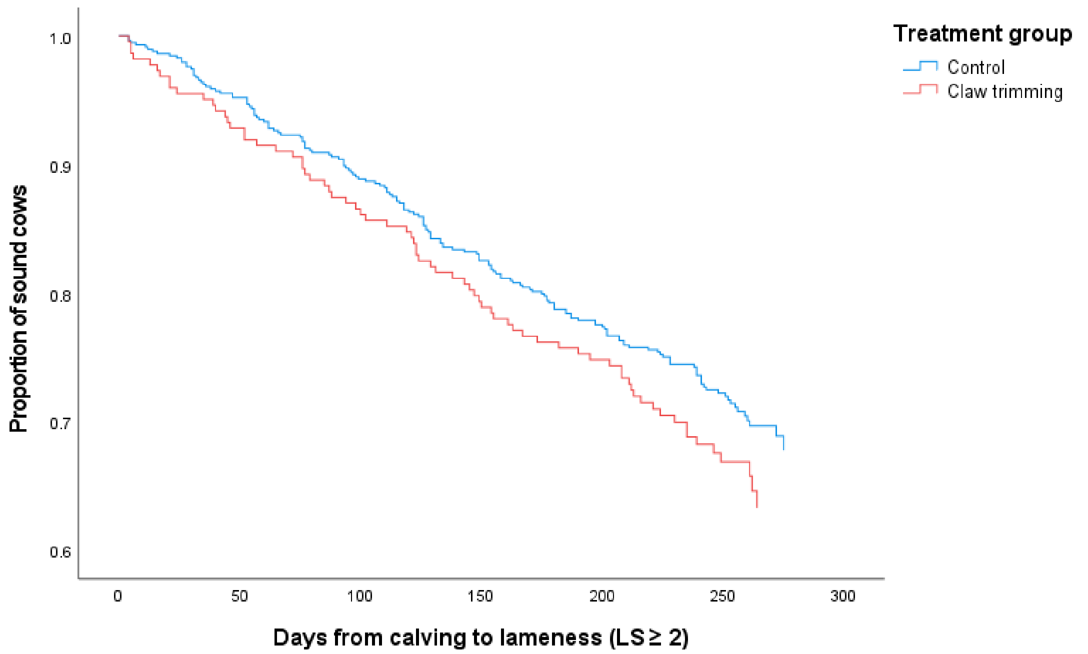

Figure 6.4: The Cox proportional hazards regression of the time from calving to lameness (LS ≥2) on one dairy farm for the 2018/2019 production season (n = 807). The age and breed were included in the model as a covariate.

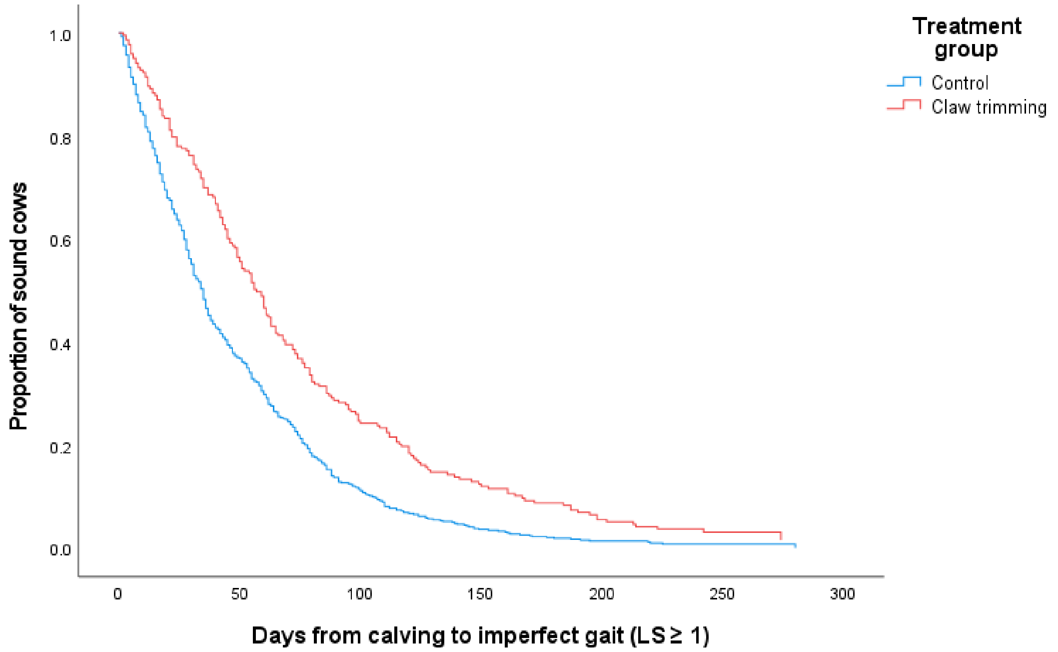

Figure 6.5: The Cox proportional hazards regression of the time from calving to imperfect gait (LS ≥1) on one dairy farm for the 2018/2019 production season (n = 807). The age and breed were included in the model as a covariate.

6.3 Discussion

The present study evaluated a three timepoint claw trimming regime on the occurrence of lameness in dairy cows kept permanently at pasture. To the authors' knowledge, this is the only study other than Bryan *et al.* (2012) to have looked at claw trimming in such cattle. Bryan *et al.* (2012 reported that while trimming did not reduce overall lameness incidence in the first 70 days after trimming, it did decrease the time to lameness (as detected by farm staff). In contrast, we found no clear benefit of trimming on time to lameness (as detected using locomotion scoring with LS≥2 being our definition of lameness). Our HR for having a locomotion score ≥2 was 0.87 (95% CI 0.66 to 1.14) for non-trimmed vs trimmed cows, whereas the equivalent HR for developing farm-staff detected lameness reported by Bryan *et al.* (2012) was 1.56 (95% CI: 1.10–2.26).

The key difference between these studies may have been the incidence of lameness. In our study farm, the incidence of cows treated for lameness was 4.3% (35/807) during the study. In contrast, despite recording lameness over a shorter period (6 months), Bryan *et al.* (2012 reported an incidence of 14.5%. The level of lameness in the present study is relatively low compared to previous reports of lameness in New Zealand, which reported incidences of 15 to 20% (Alawneh *et al.* 2012; Mason *et al.* 2012) and lower than in previous years on the study farm of ~10%. The relatively low level of lameness on our study farm may be a key reason we found no effect of trimming, as it may reflect an absence of lameness risk factors which could be ameliorated by trimming. However, looking at our data, perhaps the most important factor is the lack of differences in claw height between medial and lateral claws in many of the cows, as this is a critical target of the trimming method used in this study (Toussaint Raven 1985).

Bryan *et al.* (2012 recorded claw height differential and showed that claw height was a risk factor for lameness incidence but not for time to first lameness case. In the current study, we did not record claw height differential; however, our categorisation of the amount of trimming required was based on the foot trimmer’s estimate of claw height differential. So our no, light and medium trim categories are thus, respectively, approximately equivalent to the 0-2 mm, 3-4 mm, and >4 mm claw height differential categories used by Bryan *et al.* (2012). Our heavy category has no direct comparator as that was based on the cow having a lesion that needed a therapeutic trim. At the first trim in this study, the percentage of cows needing no trim was 52.6%, and the percentage with at least one claw needing a medium trim was 11.2% (see Table 6.4 and Figure 6.1). In contrast, Bryan *et al.* (2012) reported that 18% of their cows had no height differential (0–2 mm) in either hind foot and that 25% had at least one hind foot with a claw height differential >4 mm. Thus our study farm probably had much less claw imbalance than was observed on the farms in the study by Bryan *et al.* (2012), which may have resulted in us recording less benefit from trimming. We need more data on the distribution of claw height differentials on more herds across New Zealand and more data on whether an increased proportion of cows with large claw height differentials is associated with increased lameness risk and the success of prophylactic hoof trimming.

Unlike Bryan *et al.* (2012), we did not measure claw height differential (or assess likely trim category) in our non-trimmed group. Thus, we could not include trimming category in our analysis of the effect of trimming on the incidence of, or time to, lameness. However, the effect of trimming on time to lameness reported by Bryan *et al.* (2012) was an effect of trimming alone, as, despite claw height differential being significant in an initial univariable model, it was excluded from their final model. So it is unlikely that the exclusion of the trimming category in our model resulted in our failing to find an effect of trimming on time to lameness. Nevertheless, we believe that further research is required to establish better whether there is an interaction between the degree of trimming needed and the benefit of trimming in dairy cows kept permanently at pasture.

The aim of hoof trimming is to restore hoof conformation and balance the weight-bearing surface of the sole over the lateral and medial claws (Toussaint Raven 1985). However, there is only limited evidence as to how effective current trimming techniques are at achieving this goal, especially over the long term (Stoddard and Cramer 2017). In this study, we started with a population of cows which had never had prophylactic trimming (which is not routinely undertaken on most New Zealand farms). Thus, comparing trim categories across trimming sessions can provide information about the response to trimming in these cows. In this study population, the odds of a cow that has been routinely trimmed needing a medium/heavy trim in May 2019 (after two trimming sessions) were 2.9 times higher (95% CI: 1.89 – 4.55) than in May 2018. This was principally driven by an increase in the proportion of medium trims, 24/250 vs 44/214 (see Table 6.4 and Figure 6.1). Thus, at the end of the production season, more cows needed a medium trim (trim to correct marked claw height differential) than they did at the start of the study (when hoof conformation reflected the balance of wear and growth from environment alone). As we did not have similar results from a control group that was not trimmed, we cannot be sure that this change was solely due to trimming, but it is clear that we need more data on the long-term impact of trimming on hoof conformation in cattle kept at pasture. These studies should record the degree of trimming needed at the individual cow level. Such records would also be valuable in studies of trimming in housed cows.

Despite finding no impact of trimming on time to lameness (LS≥2), we did find an association between trimming and the interval from calving to any observable change in gait (i.e. LS≥1), with trimmed cows having a median time to LS≥1 that was 22 days longer than non-trimmed cows and a hazard of becoming unsound that was 62% of non-trimmed cows. It is unclear why we found this effect without also finding an effect of trimming on time to LS≥2, but, consistent with other data from this study, it suggests that contrary to current wisdom (Sprecher *et al.* 1997; Hut *et al.* 2021) an increase in locomotion score from 0 to 1 is not simply a step towards an inevitable increase to a score of 2 or more. In this study, 796/807 cows had at least one locomotion LS>0, of which 242 had a locomotion score≥2 or were treated for lameness. Thus, 554/796 (~70%) cows which had an elevated LS were neither treated for lameness nor had an LS>1. Thus, at least in this population, most cows which had an increased LS did not develop clinical lameness, suggesting that there are two populations of LS=1 cows: those that are going to become clinically lame and those which are not, and that delaying the development of LS=1 in the latter group does not impact on the development of clinical lameness. Further research is required to better understand the evolution of locomotion score in dairy cattle, especially at pasture, and to identify what differentiates a cow that has developed an LS=1 that is not going to progress and a cow with an LS of 1 that is going to become clinically lame.

One interesting finding from this study was that not all cows identified by the farm staff as requiring lameness treatment were identified by locomotion scoring every two weeks. Of the 35 cows identified as lame by farm staff, four had no increase in locomotion score, and 18 had a maximum score of 1 prior to their identification. Locomotion scoring and identifying cows while they are walking back to pasture after being milked is difficult (Ranjbar *et al.* 2016; Werema *et al.* 2022). So, attempting to score and identify individual cattle, irrespective of whether they were clinically lame, would have reduced the proportion of cattle we observed (Werema *et al.* 2021). However, in a study of lameness in heifers kept at pasture, where locomotion scoring was undertaken every two weeks, but identification was limited only to lame heifers (LS≥2), approximately 50% of the heifers treated for lameness were identified by farm staff prior to having an LS≥2 (Mason *et al.* 2022). This suggests that locomotion scoring every two weeks may not promptly identify all cases of lameness in cows at pasture. In contrast, in a study where locomotion scoring of cows at pasture was undertaken weekly (Alawneh *et al.* 2012), no cases of lameness were observed by farm staff before their LS was recorded as elevated by the independent locomotion scorer. Although ~20% of cows which had a maximum LS of 2 (1-5 point scale; so equivalent to LS=1 in our system) were put forward for lameness treatment by farm staff. However, further research is required to establish the optimal regime for locomotion scoring in cows kept permanently at pasture.

6.4 Conclusions

In this herd, where there was a low prevalence of lameness, and most cows needed only light or no trim, a regime of three preventative trims did not apparently decrease lameness prevalence or increase time to lameness (LS ≥2). However, it did increase the interval from calving to an observable change in gait (LS≥1). Further research is required on the impact of preventative trimming on the risk of lameness on more dairy farms across New Zealand, with particular attention being paid to the degree of trimming needed and how this affects the response to trimming.

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Chapter Seven: Evaluating the Effect of Preventative Trimming on Distance from the Sole Surface to the Distal Phalanx using Ultrasonography for Lameness Prevention in Pasture-based Dairy Cows.

Foreword: This chapter covers the study that investigated the impact of sole thickness, i.e. distance from the external sole surface to the distal phalanx (DDP) using ultrasound, on time from calving to first lameness, as well as the impact of trimming on sole thickness over time. A sub-population of thirty-eight cows was randomly selected from the treatment groups described in chapter 6, with 18 cows assigned to the ultrasound hoof trimming group and 20 cows allocated to the ultrasound non-trim group in May 2018. This was followed by monitoring sole thickness if the right hindlimb of both treatment groups at three-time points as per chapter 6. The study demonstrated that hoof trimming by an experienced trimmer using the Dutch method does not increase the risk of thin soles. The manuscript has been submitted for publication in Veterinary Sciences. In this thesis, the manuscript has been presented in journal format and style.

Article

Evaluating the Effect of Preventative Trimming on Distance from the Sole Surface to the Distal Phalanx using Ultrasonography for Lameness Prevention in Pasture-based Dairy Cows.

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Simple Summary: In pasture-based cattle, it is often suggested that claw trimming, a common lameness prevention practice in housed cows, results in thinner soles over the medium-to-long term. However, there is a lack of data on claw trimming in pasture-based cows. The aim of this study was to measure the effect of trimming on sole thickness in pasture-based cows and to evaluate the effect of sole thickness on locomotion scores. Cows were randomly selected and allocated to the ultrasound-trim and ultrasound non-trimming groups. In May 2018 (at drying off), the ultrasound-measured distance from the external claw sole surface to the pedal bone (distance to the pedal bone) was recorded. Then, trim-group cows were trimmed using the five-step Dutch method to trim the hindlimbs. These procedures were repeated during early lactation (October 2018) and the end of lactation (May 2019). The study found that trimming did not affect distance to the pedal bone and that there was no clear effect on the time to increased locomotion score. The results of this study suggest that, in pasture-based cattle, hoof trimming by a professional hoof trimmer using the Dutch method does not alter sole thickness over time.

Abstract: One common management strategy used to reduce the risk of lameness is prophylactic claw trimming. However, in pasture-based cattle, there is concern that the immediate reduction in sole thickness resulting from sole trimming will lead to medium-to-long-term reductions in sole thickness, which may increase the risks of lameness. Nevertheless, there is a lack of data on sole thickness and trimming in pasture-based cows. Therefore, the aim of this study was to evaluate the effect of trimming on sole thickness, over the medium-to-long term, as estimated using the ultrasound-measured distance from the external claw sole surface to the distal phalanx (DDP), and of DDP on the interval between calving and increased locomotion scores. Thirty-eight cows were randomly selected from a 940-cow spring calving dairy farm in the North Island of New Zealand; 18 were allocated to the ultrasound hoof trimming group, and 20 were allocated to the ultrasound non-trim group. Starting in May 2018, at the end of the 2017/18 lactation, ultrasound measurements of DDP of the right hind hoof were made on all 38 cows, and the hindlimbs of the trim group cows were trimmed by an experienced professional hoof trimmer using the five-step Dutch method. This was repeated in October 2018 (early lactation) and May 2019 (late lactation). After calving, the cows were locomotion scored fortnightly until the end of lactation using the 4-point (0-3) scale DairyNZ system. The effect of DDP on the interval between calving and first locomotion score ≥1 and ≥2 was assessed using Cox proportional hazards models, and the association between trimming and DDP was explored using linear mixed models. The results suggest that DDP has no effect on time to locomotion score ≥1 or ≥2, although the wide confidence intervals of the latter suggest that more data are needed before any definitive conclusions can be drawn. The study failed to find any clinically important impact of prophylactic trimming on DDP. This is probably related to the finding that cows with the highest DDP at the first trimming were identified by the hoof trimmer as those needing the most trimming. The results of this study, thus suggest that if the Dutch five-step method is properly applied it is unlikely to affect sole thickness over the short-to-medium term in pasture-based cattle.

Keywords: Claw trimming; claw sole thickness; ultrasonography; locomotion scoring; lameness; dairy cows

7.0. Introduction

Claw horn disruption lesions (CHDL), primarily sole haemorrhage, ulcers, and white line disease, are the major challenge to decreasing lameness prevalence on dairy farms [1, 2]. The principal cause of CHDL is contusions of the corium created by the distal phalanx [3]. The suspensory apparatus and the digital cushion are the primary structures preventing the distal phalanx from damaging the corium. The suspensory apparatus is a collection of collagenous fibrous connective tissue whose bundles are anchored in fibrous cartilage in the distal phalanx and act to transfer tensile forces to the horn capsule [4], while the digital cushion is a complex structure of fat and connective tissue that dampens and dissipates compressive forces in the heel and under the distal phalanx [4, 5]. Thus, overstraining of the suspensory apparatus caused by housing, feeding, and management conditions resulting in the suboptimal function of the suspensory apparatus [3, 4, 6] and the digital cushion [7-9] predisposes the corium to a high-pressure load leading to contusions and, subsequently, CHDL.

Various factors have been shown to influence the function of the suspensory apparatus and digital cushion. For the suspensory apparatus, the key factor affecting its function appears to be the physiological changes associated with calving, which lead to an increase in laxity and a decrease in strength of the suspensory apparatus [3, 6, 10, 11]. For the digital cushion, it seems that the most important factors which influence its function are those which affect its thickness, such as stage of lactation, parity, body condition score and inflammation within the hoof [3, 7, 8, 12, 13]. Studying such changes directly in the live animal is difficult, but ultrasonography can provide a guide to the distance between the distal phalanx and the sole surface [14-16], providing an indirect measurement of digital cushion thickness and the position of the distal phalanx within the horn capsule [13, 17-19].

One commonly recommended measure to reduce the prevalence of CHDL is prophylactic trimming which aims to restore normal claw conformation [20-24]. Most studies of prophylactic trimming have been undertaken in housed cattle, with, as far as the authors are aware, only one peer-reviewed study that has been published using data from cattle based permanently at pasture [25]. One concern associated with the use of prophylactic trimming is that it can result in thin soles, even when standard protocols are used, thus predisposing to contusions due to a lack of protection of the sensitive corium [19, 26-29]. The concern is not just that trimming can lead immediately to thin soles but that trimming can interact with abrasive environments to produce thin soles in the medium-to-long term [14, 27]. This concern about the medium-to-long term effects of trimming is prevalent in countries (such as New Zealand) which have pasture-based cattle that walk long distances from the pasture to the milking parlour at milking time, as it is considered that walking long distances on farm tracks may have the same effect as being housed in a building with abrasive flooring [30]. However, there are no data on the medium-to-long term impact of trimming on sole thickness in pasture-based dairy cattle. Therefore, the principal aim of this study was to evaluate the effect, over a lactation, of trimming on sole thickness, estimated by measuring, using ultrasound, the distance from the external claw sole surface to the tip of the distal phalanx (DDP). A secondary objective was to observe the effect of DDP at drying off on the hazard of increased locomotion score, i.e. locomotion score ≥1 (imperfect gait scores) and ≥2 (clinical lameness) in the subsequent lactation.

7.1. Materials and Methods

All the procedures in this study were approved by Massey University Animal Ethics Committee (protocol number 8/22).

7.1.1. Animals and Farm Location

The study was undertaken on a 940-cow spring calving dairy herd in the Manawatu-Wanganui region of New Zealand between May 2018 and May 2019. Most of the cows were Friesian and Jersey crossbreds, with roughly 10% Friesian cows. Animal age ranged from 2 to 10 years (mean four years). The milking cows were managed as two equal-sized groups grazed separately on the same farm, rotating around the farm's paddocks. No housing was used on this farm, cows remained permanently at pasture during the study period. Both groups were milked twice daily through a 60-unit rotary milking parlour. The average walking distance from grazing to the milking parlour was 2 km, and thus, on average, cows walked 8 km /day. On arrival at the milking parlour, the cows were gathered in the collecting yard, which had a concrete floor, until all the cows had arrived (a process that usually took ~ 30 minutes) when milking started. As milking through the rotary parlour took on average 2.5 hours, the average cow spent ~0.75 hours per milking (1.5 hours/day) standing on concrete (in the yard or the parlour).

Regular lame cow management included identification of lame cows during routine operations by farm staff, with veterinary visits to treat lame cows at least every two weeks (more frequently if required). On this farm, staff did not use systematic locomotion scoring before or during the study. Once cows were identified as lame by farm staff, they were put into a lame-cow group until the farmer determined they were no longer lame. This group was kept on a paddock (confined grazing area) close to the milking parlour and milked once daily in the morning. The farm was selected for the study on the basis of the farmer being interested in the study and the close working relationship with the veterinary practice, not on an identified lameness problem or a problem with claw conformation. The leading causes of lameness on the farm were white line disease, sole injury and foot rot. All lesions were identified using the criteria set out in [31]. Digital dermatitis had not been detected at any time before the commencement and throughout this research.

7.1.2 Visit 1 - at Dry-off (May 2018)

At the first trimming visit (May 2018), cattle in the milking herd were randomly assigned to being in one of two treatment groups (non-trim (n = 690) and trim (n = 250)). For this study, at the first trimming visit, 20 cattle in each of the two treatment groups were then randomly selected using a random allocation sheet for ultrasound monitoring of DDP. The number of cows per group was based on the number that could be measured over a three-day period and was the same as used in previous research on DDP in pasture-based cattle [13]. Cows that had an ultrasound examination were evenly spread through both milking groups and remained in their groups over the whole of the study period, except for disease management purposes.

A professional hoof trimmer employed a mobile hydraulic Wopa Pro+ Cattle Crush with accessories to restrain the cows and an angle grinder (a professional trimming disc) and Hauptner hoof trimming knives to trim the claws using the five-step Dutch method described by Toussaint Raven [32]. Trimming was undertaken for three consecutive days at each visit, with ultrasound measurements being undertaken on all three days, with cow numbers being evenly split for trimmed and non-trimmed cows. Briefly, the trimming procedure involved 1) trimming the toe length of the medial claw to 75 mm, leaving 5 to 7 mm thickness in the tip of the toe and sparing the height of the heel 2) making the lateral claw equal in length and weight-bearing surface to the medial (or as near as possible), 3) making a slope in the soles, 4) reducing the weight in the affected claw (if lesions present), and 5) removing loose horn and hard ridges.

The hoof trimmer assigned each hind foot to one of four categories: **0,** trim not required; **1,** light trim required (trim to remove the slight difference between the claw height); **2,** medium trim required (trim to correct marked claw height differential); **3,** heavy trim (correct claw height difference and treat a lesion). Both hind feet were trimmed as per standard practice, and the worst score was recorded as the score for the cow (cows' trim scores were very similar across both feet).

The ultrasound technique used in the present study was that validated by Laven et al. [17] for the equipment used in this study. Those authors found that calliper-measured sole thickness immediately below the distal phalanx was less strongly correlated to the ultrasound measurement of sole thickness at that point than to the ultrasound measurement of DDP to the tip of the distal phalanx (0.51 vs 0.8, respectively) and that the agreement between sole thickness predicted from DDP with calliper sole thickness was better than that between ultrasound sole thickness and calliper sole thickness. Thus, with the equipment used in this study, measuring DDP to estimate sole thickness is easier, quicker, and more accurate than direct ultrasound measurement of sole thickness. This method of DDP as a proxy for sole thickness has been used in the study of the outbreak of claw lesions reported by Mason et al. [15] and in the evaluation of changes in DDP in four herds in New Zealand [13]. In addition, as a previous study by Laven et al. [13] showed that DDP measurement of both hind feet did not provide useful additional information about DDP compared to one hind foot and took twice as long, only the right hind foot was examined using ultrasound.

For ultrasound monitoring of DDP, cows were restrained in a hoof crush (Wrangler, Whakatane, New Zealand). Once restrained, a cow's right hind foot was lifted, washed, and dried before measurement. The DDP was then measured at the tip of the distal phalanx of both lateral and medial claws using a portable ultrasound machine (Mindray DP 6600, Mindray, Szechuan, China) as described by Laven et al. [17]. Briefly, a linear probe was inserted into a vinyl glove containing acoustic coupling gel for protection. Then transmission gel was applied to the claw surface of the sole, followed by placing the probe along the longitudinal claw axis. The probe frequency was set to 5 MHz. Once an appropriate image was obtained, it was frozen, and a measurement from the outer surface of the sole horn to the tip of the distal phalanx was recorded alongside the cow identification number. The cow was then released, with non-trim cows being released directly to pasture and trim group cows to the head of the trimming queue.

7.1.3 Visit 2 and 3 - October 2018 and May 2019

The farmer drafted the same individual cows for the ultrasound group (US-trim and US-non-trim), and measurements of DDP were made as in visit 1.

7.1.4. Locomotion Scoring

Locomotion scoring was performed fortnightly, with cows being scored during the afternoon milking session as they exited the milking using the 4-point (0-3) scale DairyNZ lameness score [33]. The scoring procedure was as described by Werema et al. [34] and was undertaken by the first author, who was a trained locomotion scorer [34]. Cows were locomotion scored on 19 occasions between 15 August 2018 and 08 May 2019. Data were included for analysis of locomotion scores only from cows with at least four locomotion scores during that period.

7.1.5. Statistical Analyses

All data were analysed using SPSS version 27 (IBM Corporation, Armonk, New York, USA). Descriptive statistics were created for the locomotion scores, claw trimming category, and distance from the external surface of the sole horn to the tip of the distal phalanx data sets. For all models, data are reported using 95% confidence intervals (95% CI) to identify the range of effect sizes (hazard ratio (HR) and mean differences) with which our data are compatible [35].

A multivariable Cox proportional hazards regression was employed to assess the association of DDP at the first visit on time to first observed increase in locomotion score from 0 (LS≥1) and on time to first observation of clinical lameness (LS≥2). Key predictor variables in both models were the treatment group and DDP of the lateral claw and medial claw of the right hind foot at visit 1, which were forced into the model irrespective of their p-value. Age and breed category (see Table 7.1) as well as the interactions between DDP and treatment group, were also included in the model but were eligible for removal during the backward selection process if p>0.05, and their removal did not change coefficients by >20%. The impact of using both DDP of the lateral and the medial claw in the same model was assessed by measuring the resulting variance inflation factors (VIF) to ensure there was no consequential multicollinearity. Proportionality assumption was tested using visual assessment of Kaplan Meier curves, log(−log) plots, and if those were uncertain, testing the Schoenfeld residuals. Outputs from the models are reported as hazard ratios (HR) with 95% confidence intervals and interpreted as per Gelman and Greenland [35].

Two linear repeated measure mixed models were then created to assess the effect of trimming on DDP over time. The first model only used data from cows in the trimmed group. DDP was the outcome variable, cow the subject variable, visit, claw within cow the repeated measures, and trim category at visit 1 were the predictor variables. Age and breed were not used in these models as a univariable analysis had shown no association in this dataset between DDP and age or breed category (p≥0.6). All possible two-way interactions were added, and backwards selection was then used to remove any interactions where p>0.05 (all main effects were kept in the model, irrespective of p-value). The second model used data from all ultrasound-monitored cows. Again, DDP was the outcome variable, cow the subject variable, visit, and claw within cow the repeated measures and treatment group (trim vs non-trim) the predictor variables. DDP at visit 1 and calving dates was used as covariates. Again, all possible two-way interactions were added, and backwards selection was then used to remove any interactions where p>0.05 (all main effects were kept in the model). The models used were selected on the smallest values of fit statistics for the -2 Restricted log-likelihood. Outputs from the models are reported as mean differences with 95% confidence intervals and interpreted as per Gelman and Greenland [35].

7.2. Results

Initially, we aimed to enrol 40 cows, with 20 in each group (claw trim + ultrasound scanning and ultrasound scanning only). Twenty cows were scanned in the non-trim group, but 18 were scanned in the trim group (as two cows in that group were accidentally trimmed before scanning). Thus, 38 cows were scanned during visit 1, with a measurement of DDP being achievable in 74/76 claws (as two cows in the non-trim group each had only one usable image). The age, breed and calving date of the ultrasound cows in each treatment group are summarised in Table 7.1.

At visit 2, the farmer presented 32 cows (17 non-trim and 15 trim) for examination. Forty-nine usable images were obtained from the 64 claws. Finally, 32 cows (16 of each treatment group) were drafted during visit 3, with 50 usable images being obtained from the 64 claws. Detailed data on usable images acquired by treatment group and visit are presented in Table 7.2.

Table 7.1. Comparison of age, breed, and calving date between trim and non-trim groups (n = 38).

Treatment group	Age – number of cows (%)			Breed - number of cows (%)		Calving date	
	≤4 years	5 - 7 years	≥8 years	Friesian	F x J	Mean (95% CI)	Median
Non-trimmed	9 (45)	10 (50)	1 (5)	3 (15)	17 (85)	24/08/18 (14/08–03/09)	21/08/2018
Trimmed	8 (44)	9 (50)	1 (6)	2 (11)	16 (89)	17/08/18 (10–23/08)	14/08/2018

F = Friesian, J = Jersey, % = percentage, CI = confidence interval, Min = minimum, Max = maximum.

Table 7.2. Summary of the data on usable images obtained by treatment group and visit.

Visit	Group	Cows scanned	Number of usable images per cow	Cows
			0	0
1	Trim	18	1	0
			2	18
			0	0
	Non-trim	20	1	2
			2	18
			0	0
2	Trim	15	1	4
			2	11
			0	3
	Non-trim	17	1	5
			2	9
			0	3
3	Trim	16	1	0
			2	13
			0	3
	Non-trim	16	1	2
			2	11

7.2.1. Locomotion Scores and Lameness Prevalence

Data from 35 (trim group n = 17 and non-trim n = 18) cows were included in this analysis, as three cows were excluded from the analysis because they had less than four locomotion scores. The median number of locomotion scores per included cow was 15, and the interquartile range was 5. Sixteen locomotion scores of 2 (11 cows) were recorded during the study period, with no locomotion scores of 3. The mean prevalence of locomotion scores of 2 across the study period was 3.3%. Only two cows, one in each treatment group, were drafted by the farmer for lameness treatment. Once cows treated for lameness were included, all cows were recorded as having had at least one score of ≥1, and 11 (trim group n = 5 and non-trim n = 6) were recorded as having had at least one score of 2.

7.2.2. Survival Analyses

The VIF in the regression model for DDP of the lateral claw (DDP-L) and DDP of the medial claw (DDP-M) were 1.9 and 2.1, respectively (indicating a lack of consequential multicollinearity [36]). The initial models thus included breed, age, both DDP, treatment group and the two treatment group*DDP interactions. The final models included only the two DDP and treatment groups. In regard to the effect of treatment group, for the model evaluating the time to LS≥2, our data were compatible with a large range of effects, from a small decrease in hazard, through no effect, to a large increase in hazard (see HR and 95% CI in Table 7.3). For time to LS≥1, the effects of our data were compatible with a range of effects from a large decrease in hazard to no meaningful effect (Table 7.3).

Irrespective of the LS target (LS≥2 or LS≥1), neither DDP-L nor DDP-M at first measurement clearly affected the hazard of increased LS. For LS≥1, our data supported a conclusion that there was no meaningful effect as the 95% confidence interval for the hazard ratio (HR) associated with an increase in DDP of 1 mm ranged from a small decrease in hazard to a small increase (see Table 7.3). However, for LS≥2, our data did not rule out an increase in DDP of 1 mm being associated with a relatively large increase in the hazard of LS≥2 (upper 95% CI 1.77 and 2.53 for DDP-L and DDP-M, respectively).

Table 7.3. The coefficients of the predictor variables on the hazard of LS≥1 and LS≥2 (from the Cox proportional hazards model).

For LS≥2	HR	95% CI	
DDP-L	1.05	0.62	1.77
DDP-M	1.33	0.70	2.53
Treatment group (trim vs non trim)	1.34	0.35	5.15
For LS ≥1			
DDP-L	0.93	0.72	1.21
DDP-M	0.95	0.70	1.28
Treatment group (trim vs non trim)	0.45	0.20	1.03

LS = locomotion score, CI = confidence interval, DDP-L = distance to the distal phalanx lateral claw, measured during visit 1 (May 2018), DDP-M = distance to the distal phalanx medial claw, HR = hazard ratio (for DDP, this is the increase in hazard given 1 mm increase in DDP).

7.2.3. Effect of Time and Trimming Category at Visit 1

All interactions were removed before the final model was reached. In this model, there was no clear difference between mean DDP-L and DDP-M, with a mean difference of 0.42 mm (95% CI -0.10 to 0.95) (see Table 7.4a). This was consistent with the finding that in the 103 within-foot claw comparisons, DDP-L was higher than DDP-M on 54 occasions and lower on 49. In this group of trimmed cows, DDP before first trimming was smaller at visit 1 in May 2018 than in October 2018 and May 2019 (visits 2 and 3, respectively). The mean difference between visits 1 and 2 was 1.97 mm (95% CI 1.26 to 2.67), visits 1 and 3 was 1.69 mm (95% CI 1.03 to 2.33), and between visits 2 and 3 was 0.28 mm (95% CI -0.54 to 1.10) (see Table 7.4a). Trim category at visit 1 had a clear effect on DDP, with trim category 2 cows having higher DDP than trim category 1 and 0 cows (mean difference 1.54 mm (95% CI 0.26 to 2.82) and 2.03 mm (95% CI 0.71 to 3.34), respectively (see Table 7.4a).

7.2.4. Effect of Time and Treatment Group on DDP

All interactions were removed before the final model was reached. In this model, there was again no clear difference between mean DDP-L and DDP-M (see Table 7.4b). The covariate (DDP at visit 1) was significant in the linear repeated measure mixed model. For visit 2, an increase of 1 mm in the covariate was associated with an increase of 0.45

mm (95% CI 0.44 to 0.47 mm) in DDP. For visit 3, an increase of 1 mm in the covariate was associated with an increase of 0.45 mm (95% CI 0.43 to 0.47 mm) in DDP. For the trimmed group, mean DDP at visit 1 was 7.38 and 6.87 mm for lateral and medial claws, respectively. The equivalent figures for the non-trimmed cows were 8.06 and 7.88 mm, respectively. Although, in this model, mean DDP-L was higher than DDP-M, there was again no clear difference between the two measures (see Table 7.4b). Mean DDP at visit 2 in October 2018 was higher than at visit 3 in May 2019, with a mean difference of 0.6 mm (95% CI 0.13 to 1.08 mm) (see Table 7.4b). Treatment group had no clear effect on DDP though the trimmed group had a higher mean DDP than the non-trimmed group (mean difference 0.18 mm; 95% CI -0.32 to 0.68 mm).

Table 7.4. Effect of claw trimming, claw, visit, trim category, and treatment group on mean distance (mm) measured from the external sole surface to the distal phalanx on one dairy farm during the 2018/2019 production season.

a. An evaluation of the association between trim category and DDP (n = 18)

Claw	Visit	Trim category at first trimming	Estimated marginal mean	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Lateral			8.98	8.44	9.52
Medial			8.56	8.02	9.09
	1		7.55	7.05	8.06
	2		9.52	8.82	10.22
	3		9.24	8.55	9.92
		0	7.93	7.48	8.39
		1	8.42	8.05	8.78
		2	9.96	8.71	11.20

b. An assessment of the effect of prophylactic claw trimming on DDP over time (n = 38)

Claw	Visit	Treatment group	Estimated marginal mean	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Lateral			9.07	8.73	9.40
Medial			8.96	8.63	9.29
	2		9.31	8.95	9.68
	3		8.71	8.40	9.02
		0	8.92	8.56	9.28
		1	9.10	8.77	9.43

Visit: the first trimming was conducted during dry-off (May 2018), the second trimming was undertaken in early lactation (October 2018), and the third trimming was performed at the end of the lactation (May 2019). Trim category: 0 = no trim required, 1 = light trim required, 2 = medium trim required. Treatment group: 0 = non-trim cows, 1 = trimmed cows.

7.3. Discussion

The principal aim of this study was to evaluate over a lactation the effect of prophylactic trimming on DDP. The secondary aim of this study was to evaluate the influence of

DDP on the interval between calving and increased locomotion score, primarily imperfect gait (LS≥1) but also clinical lameness (LS≥2).

Our analysis found no clear effect of DDP on either time to LS≥1 or time to LS≥2. However, our data support different conclusions for the two locomotion score targets. For time to LS≥1, our data strongly support no effect, with a narrow 95% confidence interval (see Table 7.3), limiting the likely true effect of DDP to between a small decrease and a small increase. In contrast, for time to LS≥2, the large confidence intervals mean that we cannot rule out a meaningful association between DDP and time to LS≥2. Our study was limited by the number of cows which showed clinical lameness and also by the relatively high mean DDP which was higher at visits 2 and 3 than the marginal threshold of 8.5 mm suggested by Newsome et al. [12]. We need more data to better characterise the association between DDP and the risk of lameness in pasture-based cows.

This analysis used locomotion score data from only one trained scorer. Locomotion scoring is subjective in nature, and it is known that it does not have 100% specificity or sensitivity [37-39]. Thus, it is possible that this scorer could have systematically under or over scored cows. However, this bias would not have been related to DDP as the scorer did not have access to the DDP results while they were scoring the cattle.

For our principal outcome of DDP change over time and the effect of trimming on that change, we had two models: Our first model of the change in DDP over time (which included only cows in the trimmed group) evaluated the effect of time (visit 1, 2 or 3) and trim category at visit 1 (no trim required, light trim required or medium trim required) on DDP. All interactions were removed from the model as p≥0.05, so that only the main effects were included. In trimmed cows, DDP increased between visit 1 and visit 2, with little change between visit 2 and visit 3 (see Table 7.4a). It is likely that our estimate of the difference in DDP between visit 1 and subsequent visits is an underestimate, as the proportion of claws in which DDP could not be measured was higher at later visits than at visit 1. The most likely reason for being unable to image a claw is that it is thicker than 10 mm [40], so it is likely that the actual mean DDP of the cows at visits 2 and 3 was higher than our estimate.

Even excluding this potential effect, despite prophylactic trimming being used on the farm for the first time, the DDP was higher at the drying off after trimming than it had been at the drying off before trimming. Interestingly in this model, the cows with the most horn removed at visit 1 (those cows in trimming category 2) had the greatest DDP at every visit. Thus, trimming category at visit 1 was strongly associated with DDP at visit 1, and therefore the visual assessment of the need for trimming by the experienced professional hoof trimmer (using the five-step Dutch method) was closely associated with sole thickness. This meant that it was only cows with thicker soles than average which received a medium trim (extensive paring), while cows with thinner soles than average were determined to need little or no paring. As the conformational changes used to determine the degree of trim were related to DDP it was very unlikely that the prophylactic trimming used in this study would have resulted in excessively thin soles immediately after trimming.

The second model of the change in DDP over time (which included cows in the trimmed and non-trimmed groups) evaluated the effect of time (visit 2 or 3) and treatment group (no trim vs trim) on DDP and used DDP at visit 1 as a covariate. Again, no interactions remained in the final model. As in the previous model, the mean DPP at visits 2 and 3 was greater than at visit 1. Including the covariate resulted, in contrast to the previous model, in DDP being clearly lower at visit 3 than at visit 2. The covariate DDP at visit 1 was strongly associated with the DDP at subsequent visits. This finding suggests that DDP is a cow-related effect (i.e. even when mean DDP changes with time, cows that had higher DDP than average will still have higher DDP than average at subsequent time points). We found no effect of treatment on the relationship of DDP with time. In particular, this study suggests that it is very unlikely that the trimming procedure employed in this study would result in a clinically important decreased in DDP (lowest 95% CI -0.32 mm, i.e. our data suggest that it is unlikely that the true effect would be to reduce DDP by more than 0.32 mm). Thus on this farm, after sole horn was removed by trimming, the claws were able to respond by increasing horn growth and restoring most or all the lost horn [41].

Thus the changes in DDP with time (in particular, the difference in DDP between visit 1 and visit 3, which were at the same time in the lactation cycle) are not the result of trimming but differences in hoof growth and wear between years. The published literature on DDP in pasture-based cattle is limited. As far as the authors are aware, the only peer-reviewed published study is that by Laven et al. [13]. This study involved recording the DDP in 25 heifers on five occasions over their first lactation, between day 10 and 220 days post-calving. The results reported by Laven et al. [13] are not the same as ours. Firstly they found an effect of the claw on DDP, whereas we did not. Secondly, in their study, they reported that mean DDP decreased from day 10 to day 100, whereas our study reported that DDP increased between visit 1 (prior to calving) and visit 2 (mean time since calving ~50 days). These differences may partly be due to using a mixed age population of cows and heifers in the current study (our sample population ranged from heifers that were about to be dried off after their first lactation to multiparous cows being dried off for the eighth time), whereas Laven et al. [13] only used heifers in their first lactation. No effect of age on DDP was found in this study, but this study was not designed to find such an effect with age being recorded as a potential confounder rather than a predictor variable of interest). This argument also applies to another potential source of difference, breed. Laven et al. [13] used principally Friesian heifers in their study, whereas the majority of cattle in this study were Friesian x Jersey (see Table 7.1). No effect of the breed was found in this analysis, but the study was not designed to find such an effect. However, the difference between the current study and Laven et al. [13] in the change in DDP in early lactation may simply be a herd effect. Laven et al. [42] reported the results of the DDP examination of heifers in four herds and reported that DDP increased between day 0 and day 50 in one of the four herds. We need more data on DDP over time in pasture-based herds.

7.4. Conclusion

The results of the present study suggest that in pasture-based dairy cows, DDP at drying off has no effect on time to LS≥1 in the subsequent lactation, but that more data are required before conclusions can be made on the association between DDP and time to LS≥2 (i.e. clinical lameness). On this farm, DDP increased after calving and it was not affected by trimming. This may be related to our finding that in cows which were trimmed, the degree of trimming required at drying off was strongly associated with DDP over the subsequent lactation. This study has demonstrated that if hoof trimming is done correctly in pasture-based cattle, it does not result in decreasing in sole thickness over the medium-to-long term. Further studies are warranted to determine the influence of prophylactic hoof trimming on DDP in pasture-based cattle.

Author Contributions: C.W.W. and the supervisory team conceptualised the research. F.H undertook hoof trimming. L.J.L performed ultrasound scanning. C.W.W. collected data and did the initial data analysis. R.A.L. validated data analysis and suggested further analysis. C.W.W. and R.A.L. performed the final analysis. C.W.W. wrote the first draft of the manuscript, which was contributed to and finally approved by all authors. L.J.L., K.R.M. and R.A.L. supervised the project. R.L. was responsible for funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: The farmer was a client of the Massey Farm Practice and was interested in participating when informed about this project. We did not get specific written consent from the farmer as he was a client of the Massey University Practice and was happy to have the researchers on the farm.
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Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest." Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Any role of the funders in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results must be declared in this section. If there is no role, please state "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Chacha Wambura Werema
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Chapter Eight: General Discussion and Limitations

Foreword: This chapter covers the general discussion of all results of the studies contributing to this thesis. The usefulness and challenges of lameness detection methods in respective production systems are discussed. Also, the potential of prophylactic hoof trimming as a measure of lameness management is discussed.

Chapter Eight: General Discussion and Limitations

This thesis had two principal aims: 1) to evaluate and develop effective lameness detection methods for the production systems used in New Zealand and Tanzania, and 2) to evaluate prophylactic hoof trimming as a strategy for preventing lameness in pasture-based systems such as those which are commonly used in New Zealand.

8.1 Lameness Detection Methods

Two methods of lameness detection were compared to the industry standard, locomotion scoring (LS), in this study: infrared thermography (IRT) and in-parlour scoring (IPS). Infrared thermography was tested in both New Zealand and Tanzania (see chapters 3 and 5), while IPS was used only in New Zealand (see chapter 7). For IRT and IPS, this was the first time that they had been used in New Zealand, while for IRT, it was the first use in Tanzania and, as far as the author is aware, the first time it had been used in a tropical country.

In New Zealand, the comparison of LS and IRT or IPS was conducted on two farms, both of which had a rotary milking parlour. LS was conducted after afternoon milking as the cows returned to pasture, the standard time for locomotion scoring on New Zealand farms (Fabian *et al.* 2014). On these farms, the rotary parlour design meant that cows exited the parlour individually, as compared to herringbone parlours, where cows exit as a group. When locomotion scoring cows at pasture, there is no control over cow movement, and cows walking together and obscuring each other limits the observer's ability to identify and score all the cows. Thus, LS is easier on farms with a rotary parlour than on those with a herringbone parlour, as at least at the start, cows are individually separated. Nevertheless, recording an individual locomotion score for every cow was impossible on either of the study farms.

On farm 1, the milking herd was ~1200 cows. In the three monthly scoring sessions from September to November, the average number of cows for which an individual locomotion score was recorded was 765, i.e. 64% of the herd was individually scored. On farm 2, the milking herd was about 400 cows, and the average number of cows for which an individual locomotion score was recorded in the three monthly scoring sessions from September to November was 298, i.e. 75% of the herd was individually scored. The large difference between the two herds suggests that LS with individual identification may be more feasible on smaller herds, but this suggestion needs to be tested on more herds. It is likely that if, rather than attempting to identify individual locomotion scores for all cows, only cows with a score of 2 or more (clinically lame) had been individually identified, a higher proportion of cows would have been scored. Unfortunately, this approach was not feasible in this study as we needed individually identified cows across the range of locomotion scores. However, this approach was used by Mason *et al.* (2022) in their study of lameness in heifers in New Zealand, and it is recommended by the AHDB (who developed the locomotion score, which is the principal source for the DairyNZ lameness score). In contrast, although the DairyNZ lameness score was developed from the AHDB score, it recommends individually recording cows with a locomotion score of 1 (imperfect gait), so they can be monitored. The data from this thesis suggest that this should be changed (at least for routine locomotion scoring).

Nevertheless, irrespective of the recording method, whole herd locomotion scoring is significantly time-consuming. A staff member needs to be specifically allocated to the task at a time (during milking) when staff availability is limited. Thus methods of lameness detection, which can potentially be automated (e.g. IRT) or undertaken alongside other milking-related tasks (e.g. IPS), may be useful, particularly in the New Zealand market.

In contrast, it was possible to score the whole milking herd during milking in Tanzania. This scoring was feasible principally because of the relatively small herd size (<70 milking cows on the studied farms) and because the flow rate of cows exiting the milking parlours was relatively slow, even though most farms used herringbone parlours. However, accurate LS does require significant training, which may be challenging to achieve, especially on smaller farms. Training livestock advisors may be a potential route, but this would require significant government funding to train advisors and support them in ongoing LS.

8.1.1 Infrared Thermography

IRT was shown to be an effective method of lameness diagnosis in both New Zealand and Tanzania. Compared to the reference standard LS, in New Zealand, IRT had a sensitivity (Sn) and specificity (Sp) of 80% and 92.4%, respectively. In contrast, in Tanzania, IRT had a Sn and Sp of 73.2% and 86%, respectively. Despite Sn and Sp being lower in Tanzania than in New Zealand, the positive predictive value (PPV) of IRT in New Zealand was lower (~ 63%) than in Tanzania (72%). This difference is driven by the prevalence of lameness (locomotion scores of ≥2) in the two study populations, with Tanzanian farms having a higher lameness prevalence (33%) than New Zealand (14%). PPV is a key driver of farmer acceptance; if cows are identified as lame but are found not to be lame on examination, farmers may begin not to trust results from the alternative to LS (O'Leary *et al.* 2020).

Under New Zealand conditions, if these data are representative, our PPV suggests that IRT needs to be followed by an additional assessment before feet are lifted, as 1/3 of all cows identified as lame by IRT did not have an elevated locomotion score. This is likely to reduce farmer buy-in, especially with the large herd size in New Zealand. In contrast, under Tanzanian conditions, the PPV obtained was moderate because approximately 25% of all cows detected as lame did not have an increased locomotion score. However, given Tanzania's relatively small herd size and limited effective lameness detection methods, farmers and their livestock advisors are likely to look more favourably on IRT for lameness detection. Nevertheless, improvements in the specificity of IRT are needed before it can be used for routine lameness detection.

In both countries, our analysis identified that the mean foot skin temperature (i.e. the mean of the measurements from all 14 zones of the plantar aspects of both hind feet) was the optimal temperature measurement. This measure is simple to calculate, so it seems to be suitable for ongoing use as the IRT measure. Our research identified significant differences between New Zealand and Tanzania in optimal cut-off temperature. In New Zealand, the cut-off point for mean temperature was lower (34.5°C) than the cut-off point in Tanzania (38.0°C). The geographical location of these countries likely explains this difference as the mean daily temperature in New Zealand was 15°C, while in Tanzania, the average temperature was around 30°C. This difference highlights the importance of setting flexible thresholds for lameness diagnosis, perhaps even on an individual farm basis. This varying cut-off point is much more likely to be achievable in New Zealand, where IRT automation is key to its future use.

In contrast, in Tanzania, automation is unlikely to be a feasible approach in even the medium term, so if it is going to be used, IRT will need to be used by the individual farmer on individual cows. An immediate issue is the lack of awareness concerning lameness and its impact on dairy farms by both farmers and livestock advisors. So, a campaign for awareness creation among key stakeholders will be essential if IRT is to be used. However, the cost of IRT is currently a major limitation, which makes IRT use completely unfeasible on Tanzanian dairy farms. However, the cost of IRT technology is decreasing, and IRT is now available through smartphone apps, e.g. FLIR (https://bit.ly/3TUIm11). Currently, such technology may not be sufficiently accurate enough for diagnostic use on its own (Kirimtat *et al.* 2020), but smartphones are common in Tanzania. Furthermore, as the technology improves and becomes more affordable, it is possible that IRT could become feasible, especially as smartphone technology will allow the IRT to be used to determine lameness risk based on a built-in algorithm, eliminating the need for farmer interpretation.

8.1.2 In-parlour Scoring Procedure

The In-parlour scoring (IPS) procedure was developed by adapting the stall lameness scoring proposed by Leach *et al.* (2009), which was developed for and has been tested in tie-stall cows (Leach *et al.* 2009; Gibbons *et al.* 2014; Palacio *et al.* 2017). We used two methods of analysing the data obtained by the IPS procedure (i.e. conventional and machine learning). Conventional analysis is relatively simple and easy to interpret, while machine learning is complex and requires software and expertise to analyse and interpret the results. In our study, we found that employing a cut-off of ≥2 positive indicators had an optimal sensitivity of >92% and specificity of >98% for detecting higher locomotion scores of ≥2 (clinical lameness). On the other hand, the optimal decision tree machine process was based on correctly categorising cows as having locomotion of 0, 1, or ≥2, resulting in a true positive rate (sensitivity) of detecting cows with a locomotion score of ≥2 of 75% and a false positive rate (1-specificity) of 0.2%. The lower sensitivity of the machine learning is because we were aiming to predict locomotion score category accurately, not just < or >2, but as machine learning has the ability to use more data from different sources such as milk yield, live weight, and animal behaviours (Borghart *et al.* 2021) there is the possibility of improving these parameters by combining IPS with more data. Nevertheless, both results clearly show that IPS has a specificity high enough for it to be used to identify cows for treatment without further testing.

The key problem with IPS was that under New Zealand conditions, it required significantly more time than LS, though cow identification was relatively easier (Werema *et al.* 2022). If the IPS procedure is to be done routinely, rotary speed needs to be reduced, as it is during pregnancy diagnosis, to allow more cows to be scored. Additionally, IPS needs testing on herds with a herringbone parlour to assess how it fares in this system. Finally, further research is required to establish whether we can speed up IPS without compromising accuracy.

The IPS technique developed in this thesis could be a valuable lameness detection procedure in different management systems, including in tropical countries such as Tanzania, where a suitable area for LS may not always be available. Although as with LS, it will need trained staff (or farmer training) to become useful. However, further testing and optimising of the IPS protocol for different production systems is warranted.

8.2 Prophylactic Hoof Trimming

Prophylactic hoof trimming has been identified as a key intervention for reducing non-infectious lameness (Manske *et al.* 2002; Bryan *et al.* 2012; Sadiq *et al.* 2021). The studies contributing to this thesis focused on the impact of prophylactic trimming (at three timepoints during the lactation cycle) on the time to increased locomotion score and its impact on the protection of the sole corium (as estimated using ultrasound measurement of the distance from the external claw sole surface to the tip of the distal phalanx (DDP)). Our data provide clear evidence that on the study farm, trimming did not have a clinically relevant impact on lameness prevalence (i.e. the proportion of cows with locomotion score ≥2) or on the interval between calving and clinical lameness. However, trimming increased the interval between calving and locomotion score ≥1. It is unclear what the impact of this increase is on either cow welfare or productivity. Further research on more farms across New Zealand is needed.

One major concern, especially in pasture-based cows, is that trimming will increase the risk of thin soles. In the trimmed group, cows with the largest DDP were identified as requiring a medium trim, and those with the lowest DDP as not requiring a trim. This effect of a trim category at visit 1 persisted over the whole lactation. These results strongly suggest that over trimming is not likely to occur in pasture-based cattle when trimming is performed by a trained and experienced hoof trimmer/veterinarian using the Dutch five-step method.

We also evaluated the association between DDP and the onset of lameness. In contrast to trimming, we found no association between DDP and interval to a locomotion score ≥1. For locomotion score ≥2, we also found no statistically significant association, but we had too few cows with scores ≥2 to characterise the association properly. More data are needed to understand the impact of DDP on lameness in pasture-based cows.

Based on the results of the present study, although we found no evidence that trimming adversely affected sole thickness, we also found no evidence that it was useful in reducing the time to lameness. The lack of benefit could be the low number of claw conformation issues identified on the study farm, with more than 50% of the cows not requiring hoof trimming on either hind foot at the first trimming occasion. Further data are required from farms where hoof trimmers regularly identify the need for trimming a higher percentage of the herd. Such research should look at whether there is a threshold of cows needing to be trimmed before whole herd trimming is economically beneficial and how this can be identified without examining the lifted feet of a large proportion of the herd.

It is not only prophylactic trimming where we lack data on the effectiveness of preventative lameness strategies on New Zealand farms. Although we have high quality data on risk factors for lameness (Chesterton *et al.* 1989), this data is now over 30 years old, and we have no data on how effective preventative strategies based on that data are at reducing the risk of lameness. Also, we lack lameness prevalence data; the recently available data is more than eight years old (Fabian *et al.* 2014). We even lack data on the association between a lameness event and subsequent lameness problems. In housed cows, previous lameness is a key predictor of future lameness (Reader *et al.* 2011; Huxley 2013), probably because of because of irreversible lesions such as the formation of bone exostoses on the pedal bone (Newsome *et al.* 2016). However, this has not been shown to occur in pasture-based cows.

Therefore, more research is needed on the impact of hoof trimming as a means of lameness management in cattle kept at pasture permanently, as in New Zealand.

8.3 Limitations of the Thesis

8.3.1 Locomotion Scoring as a Benchmark Method

Locomotion scoring has limitations that reduce its effectiveness (O'Callaghan 2002; Flower and Weary 2006, 2009). In pasture-based systems, large herd and environmental factors make LS more challenging (Fabian *et al.* 2014; Ranjbar *et al.* 2016; Werema *et al.* 2022). However, LS was employed in these studies as a reference standard, so our calculations of the value of alternatives to LS are based on assuming LS is a 'gold standard'; i.e. it has 100% specificity and sensitivity. This limitation could be dealt with by using a latent class analysis (Yang *et al.* 2022), which does not assume that the reference standard is a gold standard. As far as the author is aware, such an analysis has not yet been published in any peer-reviewed publications and was beyond the scope of this thesis.

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Chapter Nine: Future Studies and Main Conclusions

9.1 Future Studies

1) Evaluate LS systems in Tanzanian dairy farms to determine the most suitable system. Modifications can be made to the existing LS systems to simplify them so that they become more friendly to the farmers with limited knowledge about lameness. For example, a 4-point scale (0-3) DairyNZ becomes a 3-point scale (0-2) by combining scores 2 and 3 as score 2.
2) Further studies to establish lameness prevalence on more farms across Tanzania and determine the prevalence of key infectious diseases causing lameness, such as digital dermatitis.
3) Conduct further studies of IRT versus LS and IPS vs LS on more farms with rotary and herringbone milking parlours across New Zealand.
4) Determine the feasibility of using IRT on repeated measurements on individual cows over time (which will necessitate automation of thermal imaging). Such studies should explore using a latent class analysis that does not assume another detection method/technique is a benchmark.
5) Determine the appropriate indicators and test IPS procedure in Tanzanian dairy cattle against other lameness detection methods such as LS and IRT.
6) Investigate the association between IPS and hoof lesions, especially in cows with a locomotion score of 1 and two IPS indicators.
7) Evaluate the long-term impact of hoof trimming on hoof conformation in cattle kept at pasture and precisely determine the degree of trimming needed at the individual cow level.

8) Assessing the effect of walking on hoof growth and wear, an abrupt transition between pasture and concrete in the milking facility in cows kept at pasture permanently.
9) Evaluate the impacts of therapeutic hoof trimming over time in more New Zealand dairy cattle.

9.2 Conclusions

In New Zealand, LS has been put forward as a means of early detection of lameness. Our study suggests that the approach needs modifying only to record cows with a score of 2 or 3 and tally the rest (as is recommended in the UK). However, our data suggest that even if cows are observed every two weeks, combining locomotion scoring with less systematic but more frequent farmer observation will identify cows earlier. In contrast, there is no industry programme promoting LS in Tanzania, but the approach of recording after milking by a trained observer was effective at scoring and identifying all cows. Further research is required to establish the proportion of Tanzanian dairy farms which are suitable for this approach or whether scoring of housed cows will be necessary on many farms. However, our results indicate that if sufficient observers can be trained, then LS may be applicable on Tanzanian farms.

This study used infrared thermography (IRT) and in-parlour scoring (IPS) lameness detection as alternatives to LS. On New Zealand farms, IPS accurately identified lame cows; however, only a small proportion of the herd was examined in the time available, so further refinement of the technique is needed. IRT was reasonably effective at distinguishing clinically lame from non-lame cows. However, in New Zealand, it needs to be faster and automated in order to become useful, whereas, in Tanzania, it needs to be cheaper. Nevertheless, our studies support further research and development of IRT in both countries.

On the study farm, prophylactic hoof trimming did not reduce lameness incidence or time to clinical lameness (locomotion scores ≥2). Thus on this farm, there was no convincing evidence that prophylactic hoof trimming was of value. However, the study showed that when undertaken by an experienced professional, hoof trimming did not increase the risk of thin soles. In summary, this thesis has extended our knowledge concerning lameness detection and management in dairy cattle in New Zealand and Tanzania while at the same time highlighting the urgent for more research in both systems.