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Evaluation of a risk assessment questionnaire in identifying facility and management factors associated with dairy cattle lameness in Alberta

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by

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Abstract

A score-based lameness risk assessment questionnaire (RAQ) was conducted on 65 dairy farms in addition to the assessment of lameness and foot lesion prevalence, both infectious and non-infectious. Within-herd prevalence of lameness was 20%, remaining unchanged since the last assessment of lameness. Accuracy of the RAQ in identifying overall risk on farm was evaluated and determined to be inadequate with weak associations between total RAQ scores and lameness and lesion prevalence. When analyzing each question in the RAQ, 21 questions identified risk factors that were associated with lameness and lesions. After adjustment of the risk scores of categorical answers, the association between herd lameness and lesion prevalence and total RAQ scores improved but remained suboptimal. However, the questions that did identify risk factors can be used to support producers in prioritizing implemented changes for lameness control and mitigation.

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Dedication

TO MY PARENTS, MARTIN AND CAROLINE VAN HUYSSTEEN

For their unconditional love, support, and encouragement

in my pursuit and completion of this research

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List of Abbreviations

CDCP	Canadian Dairy Code of Practice
DFC	Dairy Farmers of Canada
NFACC	National Farm Animal Care Council
RAQ	Risk Assessment Questionnaire
HACCP	Hazard Analysis Critical Control Point
WCCHTA	Western Canadian Certified Hoof Trimmers Association
DD	Digital dermatitis

Chapter 1: INTRODUCTION

1.1 Canadian Dairy Industry

The Canadian dairy industry, along with most dairy industries worldwide, has undergone considerable change over the years through the progression in knowledge and technology towards overall increased productivity, with larger herd sizes, fewer farms, and fewer cows with increased milk production per cow due to selection of favorable traits (Barkema et al., 2015). In just the last 15 years, Canada has seen a 34% decline in the number of dairy farms with an 8% decline in the number of dairy cows, with higher total production (Canadian Dairy Information Centre, 2018). As the dairy industry in western Canada has become increasingly comprised of larger business-like corporation farms, with fewer small family run farms, animal welfare has grown to be of larger concern following the major shifts in housing systems and management practices (Barkema et al., 2015). Canada has continued to support and encourage the health and welfare of cattle as the industry has intensified. The welfare of an animal is defined as an indicator of how well an animal copes, or its state, in a given environment and accompanying conditions (World Organization for Animal Health, 2008). The 'Five Freedoms' were developed by the Animal Welfare Committee (AWC) as a means of additionally defining what a 'good state' of welfare includes; freedom from thirst and hunger, freedom from physical and thermal discomfort, freedom from pain and injury, freedom to express normal behavior, and freedom from fear or distress (AWC, 1993). The National Farm Animal Care Council (**NFACC**) is an organization that strives for exceptional animal care across all production animal industries within Canada, and among the many developed codes of practice, includes the Canadian Dairy Code of Practice (**CDCP**). This code contains recommended best practices for everything related to the handling and care of dairy cattle, including 6 sections: accommodation, housing, and

handling facilities; feed and water; health and welfare management; husbandry practices; transportation; and euthanasia (National Farm Animal Care Council, 2009). Due to the increasing importance and awareness of animal welfare, the Dairy Farmers of Canada (**DFC**) have more recently developed a mandatory initiative, proAction, that demonstrates responsible milk production to consumers and the public. The program consists of 6 modules, some of which have not yet been implemented: milk quality, food safety, animal care, traceability, biosecurity, and environment (Dairy Farmers of Canada, 2015). These programs show the importance that the Canadian dairy industry places on animal care as a priority while overall productivity continues to increase.

1.2 Lameness

Cattle lameness, best described as an abnormal gait or limp commonly indicative as a clinical sign of pain or discomfort, remains to be an important issue among dairy industries worldwide. Within Canada, it is the third most common reason for culling, after reproductive performance and mastitis (Canadian Dairy Information Centre, 2018). The economic impact of lameness is amplified furthermore by negatively affecting milk production (Green et al., 2002; Reader et al., 2011), reproductive performance (Machado et al., 2010; Chapinal et al., 2013b), and the longevity of a cow (Booth et al., 2004). In addition, its association with pain has made the issue of lameness a concern for the welfare of a dairy cow, through its disruption of the five basic freedoms (Whay and Shearer, 2017). Mean lameness prevalence within North America reportedly ranges from 15 – 55% with a large Canadian study reporting an overall prevalence of 21% (von Keyserlingk et al., 2012; Solano et al., 2015; Westin et al., 2016). Furthermore, in Canada, lameness prevalence estimates have been reported in British Columbia (28%), Alberta

(19%), Ontario (22%), Quebec (24%), and Prince Edward Island (21%) (von Keyserlingk et al., 2012; Solano et al., 2015; Jewell et al., 2019). With lameness being a worldwide health issue, we see consistent estimates within the range of reported prevalences among other countries in free stall housed systems, such as Brazil, UK, China, and Malaysia (Chapinal et al., 2014a; Sadiq et al., 2017; Costa et al., 2018; Griffiths et al., 2018). Region and housing system can affect lameness, whereby parts of the world that are mainly pasture-based systems seem to have lower lameness prevalence, such as New Zealand with a reported 8% lameness prevalence (Fabian et al., 2014). However, in free stall dominated systems within North America, there are consistent lameness prevalence estimates that are much higher than is considered as acceptable in the CDCP, stated as 10% or less (National Farm Animal Care Council, 2009). With an average prevalence being double that amount in Canada, the issue of lameness has led to the requirement of all Canadian farms to complete mandatory assessments of lameness in the animal care module of DFC's proAction program (Dairy Farmers of Canada, 2015). Farms that fail these assessments must implement corrective actions immediately.

1.3 Causes of Lameness

The dominance of free stall housing systems over tie stalls is apparent in the western provinces of Manitoba, Saskatchewan, Alberta, and British Columbia with 62, 88, 93, and 96% of farms having free stalls, respectively (Canadian Dairy Information Centre, 2018). Along with the intensification of management and larger herd sizes, free stall housing has been associated with increased risk of varying herd health issues, including lameness (von Keyserlingk et al., 2012; Barkema et al., 2015). Lameness is a multifactorial health issue, however, 90% of lameness cases are associated with the presence of a foot lesion (Murray et al., 1996). While this

association seems indicative of foot lesions being the primary cause of lameness, the complexity of this association is apparent when a cow with a lesion may not necessarily be lame (Manske et al., 2002). Nevertheless, majority of research focusing on risk factor identification for lameness has also focused on that of foot lesions. There are two categories of foot lesions, including infectious lesions which affect the foot skin, and non-infectious lesions which affect the claw-horn capsule. Digital dermatitis (**DD**) is the most common infectious lesion in varying dairy industries worldwide, and in Alberta specifically, is prevalent in 94% of herds and 15% of cows (Solano et al., 2016a). As part of the same study, the most common non-infectious lesions identified were sole ulcer, prevalent in 92% of herds and 6% of cows, and white line disease, prevalent in 93% of herds and 4% of cows (Solano et al., 2016a). These common lesions have multiple management and facility related factors that increase their likelihood of occurrence, and thus increase the likelihood of lameness. Risk of infectious lesions, mainly DD, has been associated with poor environmental cleanliness, footbath management and design, and internal and external biosecurity practices that increase the risk of within- and between-herd transmission of infectious pathogens (Relun et al., 2013; Cook, 2017; Oliveira et al., 2017; Solano et al., 2017b). Factors that increase the risk of non-infectious lesions are related to stall comfort, floor type and slipperiness, standing time, and stocking density (Leonard et al., 1996; Solano et al., 2015; Solano et al., 2016b). Lying time is also considered to be associated with lameness and is negatively impacted by sub-optimal stall comfort and design (Cook et al., 2004; Solano et al., 2016b). Adding to the management and facility related factors that increase the risk of lesion development and lameness, there are cow-level factors that are also important to consider that can support producers in monitoring and preventing the more susceptible animals from becoming lame. Parity increases the odds of a cow being lame, whereby second, third, and fourth or higher

lactation cows are 1.6, 3.3 and 4 times more likely to be lame than first lactation cows (Solano et al., 2015). Plausible reasonings are that older lactation cows have more body weight and pressure to exert on the claw and increased likelihood of repeated lesions that aids in the development of chronic lameness (Sarjokari et al., 2013). The latter can be further supported by the apparent link between abnormal bone growth on the distal phalanx when claw-horn lesions are not treated in a timely manner, predisposing the cow to experience future lesion and lameness events (Newsome et al., 2016). Previous lameness events are also becoming increasingly important in the prediction of future lameness events (Randall et al., 2018), which could be due to poor recovery and more susceptibility of a cow becoming lame again. While the odds of sole ulcers and white line lesions increase with lactation, it is interesting to note that the odds of DD are highest in first lactation cows (Solano et al., 2016a). Body condition score (BCS) has also been associated with lameness with higher odds for thinner cows defined as having a score of ≤ 2.5 (Solano et al., 2015; Jewell et al., 2019). This was thought to be linked to thickness of the digital cushion, a layer of adipose tissue between the distal phalanx and corium for shock absorption, with thinner cows having thinner digital cushions, thus reducing that ability and resulting in a higher likelihood of claw-horn lesions (Bicalho et al., 2009). However, another study added complexity to this association after determining that cows with a thinner combined layer of the digital cushion and corium had increased odds of future lameness events, but further thinning over time had no impact (Newsome et al., 2017). In summary, risk factors for lesions and lameness at the cow level need to be considered in addition to risk factors related to facility and management for increased understanding of what causes lameness.

1.4 Lameness Detection

There are many different approaches used in the detection and assessment of cattle lameness, with up to 25 manual locomotion scoring systems (MLSSs) and up to 15 automatic locomotion scoring systems (ALSSs) (Schlageter-Tello et al., 2014). The former has been the most commonly used scoring method with no added expense that only requires trained personnel to visually assess the gait of a cow. However, the resulting consequence of MLSSs is that they are a subjective measure which can impact the consistency in lameness prevalence estimates. The incline in ALSSs is due to the interest in making the assessment of lameness an objective measure to improve consistency, as well as aid producers in a more time-efficient strategy to detect lame cows in their herds. Though after using MLSSs as the reference in sensitivity measurement of ALSSs, they are considered to be poor in the detection of lameness cases and will need further research towards their improvement before being selected as the preferable method (Schlageter-Tello et al., 2014). While MLSSs remain the best method currently used in the dairy industry, there is still the challenge of how many different scoring systems there are with varying criteria and the implications they have on defining a lame cow (Van Nuffel et al., 2015). The inconsistencies between locomotion scoring systems along with being a subjective measure creates an unclear understanding of what the definition of a lame cow is for producers, which can be problematic in the detection and treatment of lame cows, leading to underestimation of the issue in their herds. Examples of criteria used in lameness case-definitions assessed visually include head bob, stride length, limp, limb abduction, arched back, and gait symmetry. Most commonly, MLSSs assess lameness with an ordinal scale based on the observational characteristics and can vary from a 2-point to 13-point scale (Schlageter-Tello et al., 2014). In Canada the most used and recognized scoring system is a 5-point scale that was

modified by the Animal Welfare Program at the University of British Columbia (Flower and Weary, 2006) and developed for the CDCP. Additionally, this scoring system is used by animal care assessors in the mandatory proAction program previously described. Due to producer familiarity of this scoring system and wide use nationally, this scale was purposefully selected for lameness assessment of dairy cattle in the current thesis research.

1.5 Producer Perception

The control and prevention of lameness in dairy cattle depends on the adoption of mitigation strategies by producers. However, a problem that has been recognized in dairy industries worldwide is the reduced ability for producers to detect lame cows, leading to underestimation of prevalence in their herds. In a Canadian study, mean lameness prevalence estimated by producers was 13% less than the mean prevalence estimated by researchers (Cutler et al., 2017). This result is especially surprising, given the producers in this study mentioned that monitoring the herd for lameness was a part of their everyday routine (Cutler et al., 2017). A study in the UK reported a similar contrast in lameness prevalence estimates and producer disagreement regarding which cows were defined as lame according to the researchers (Leach et al., 2010). This group then raised the thought that producers may be underestimating lameness in their herds because they are around their cows all the time and potentially lose sight of what the gait of a sound cow should look like. The likelihood of producer intervention with mitigation strategies will likely increase when the full extent of the health issue is acknowledged (Ritter et al., 2017). Therefore, minimization and lack of awareness of the problem can be considered a barrier towards producer efforts in the control and prevention of lameness. Another potential factor that may determine producer intervention is not only the severity in their own herd but

whether it is also a common issue for other herds in the industry (Brennan et al., 2016). With lameness being a common issue worldwide, this most likely plays a negative role in the motivation of producers to intervene. Even after a producer's decision to intervene, there are other potential barriers that could discourage them, such as the time it takes to see improvement in lameness prevalence or effectiveness of the intervention (Bruijnis et al., 2013). The complexity that producer perception adds to lameness prevention and control is something to consider in this field of research, especially when change is dependent on their actions.

1.6 Risk Assessment Questionnaire

Research on the risk factors for lameness and foot lesions has been conducted for many years proceeded by communication of results to producers, and yet lameness prevalence is still consistently high. However, when asked about the varying risk factors, producers have shown to be knowledgeable on the topic (Cutler et al., 2017). This added unclarity on why mitigation strategies are not being implemented was then followed by the idea that producers are perhaps not recognizing the presence of risk factors on their farms, specifically. Two studies that conducted thorough assessments on dairy farms to identify farm-specific risk factors for cow comfort and lameness determined that exposure to the assessment alone (Chapinal et al., 2014b), and identification of risk factors followed by directed intervention strategies (Morabito et al., 2017) were beneficial in the reduction of prevalence. Although a positive result, the amount of time required for these assessments to be done would not be practical when applied to dairy farms, outside the research setting. In Alberta, this issue was addressed by Alberta Milk and their Lameness Reduction Initiative through development of a veterinarian-administered lameness risk assessment questionnaire (**RAQ**) (Alberta Milk, 2016). The questions within the RAQ follow an

ordinal score-based structure in the identification of farm-specific risk of lameness, where a higher score indicates higher risk and vice versa. Development of the RAQ was intended to support producers in the ignition of discussion with their advisory team on the topic of lameness in the herd and where improvement can be made. The RAQ is a Hazard Analysis Critical Control (**HACCP**) approach towards the prevention and control of lameness. Food product safety was the initial purpose for application of the HACCP method, with focus on identifying the critical control points during manufacturing, and to intervene with corrective action once identified to prevent future problems such as contamination (Majewski, 1992). Since the quality of livestock production is considered to also include the health of the animal (Noordhuizen and Welpelo, 1996), the HACCP method is becoming increasingly utilized in its application to animal health and welfare problems, including that of the dairy industry. Examples include the HACCP-development of a mastitis control program in Ireland and a lameness control program for heifers in the UK (Bell et al., 2009; Beekhuis-Gibbon et al., 2011b). In Canada, there are also similar approaches in the development of control programs for Johne's disease through the use of a veterinarian-administered risk assessment to identify critical risk areas for which corrective action should be implemented (Sorge et al., 2010; Wolf et al., 2014). The RAQ to be analyzed in the current thesis research, is composed of questions regarding the management of the herd and the facility design of pregnant heifer, dry cow, and lactating cow housing to determine the level of risk for infectious and non-infectious causes of lameness.

1.8 Thesis Rationale and Overview

The overall aim of this thesis was to evaluate the newly developed RAQ in its identification of farm-specific risk for lameness and foot lesions followed by the quantification

of risk factors to further determine which risk factors have a larger impact on lameness and lesions in Alberta free stall barns.

In Chapter 2, overall accuracy of the RAQ is assessed by comparing the total scores with herd-lameness and -lesion prevalence. The RAQ would be considered accurate if herds with higher cumulative scores have high prevalence and herds with lower scores have low prevalence, in other words, a strong positive association. A RAQ and lameness assessment was conducted on 65 dairy farms, and hoof trimming records were collected to assess lesion prevalence. The results of this chapter will provide an update on the prevalence of lameness and lesions in Alberta and describe the associations between 1) presence of a lesion and lameness, and 2) total RAQ scores and lameness and lesion prevalence as a measure of its accuracy in risk identification.

In Chapter 3, risk factors provided in the RAQ will be analyzed to determine which factors have the largest impact on lameness and lesion prevalence, followed by the adjustment of related risk scores in the optimization of the RAQ to better identify overall on-farm risk. Data analyzed were collected from the same 65 herds. The results of this chapter determine risk factors most associated with lameness and lesions and the effect of changing their risk scores on the total RAQ scores and resulting associations with prevalence. Prioritization of risk factors over others can provide additional support to producers in the decision of what implementation strategies would be of most benefit to the control and reduction of lameness in their herds.

1.9 Research Questions

This thesis aims to answer the following research questions:

1) How well does the developed RAQ accurately identify the overall risk for lameness and foot lesions?
2) How can the identification of risk factors presented in the RAQ support its optimization in identifying overall risk for lameness and foot lesions?

Chapter 2: ASSOCIATION BETWEEN LAMENESS RISK ASSESSMENT AND LAMENESS AND FOOT LESIONS ON DAIRY FARMS IN ALBERTA, CANADA

2.1 Abstract

Lameness is a health and welfare concern of dairy cattle with high prevalence in North American herds. As a practical and farm-specific approach towards its mitigation in Alberta, Canada, a veterinarian-administered score-based lameness risk assessment questionnaire (RAQ) was developed; however, its accuracy in identifying risk for lameness and hoof lesions has not been evaluated. Our objectives were to: 1) provide an update on prevalence of lameness and hoof lesions in Alberta free stall herds; 2) determine the association between presence of a hoof lesion and lameness; and 3) validate the RAQ by determining the association between RAQ scores and herd-lameness and herd-lesion prevalence. For the first and third objectives, 65 Alberta dairy farms were visited between March and October 2018 to collect a completed RAQ, hoof trimming records from their hoof trimmer and video footage of the entire lactating herd. For the second objective, 10 participant herds were visited twice between November 2013 and June 2014 to take video footage of the entire lactating herd and collect hoof trimming records from their hoof trimmer within 48 hours after video footage collection. Median herd-level lameness prevalence was 20% (range = 2 – 56%), infectious lesion prevalence was 10% (range = 0 – 49%), and non-infectious lesion prevalence was 15% (range = 2 – 39%). Of cows that were lame, 93% had a lesion, whereas 21% of cows with a lesion were lame. Cows with an infectious and non-infectious lesion were 1.5 and 3.1 times more often lame than cows with no lesion. Total RAQ score and herd lameness prevalence (r = 0.26), and non-infectious RAQ score and non-infectious lesion prevalence (r = 0.45) were correlated, whereas infectious RAQ score and infectious lesion

prevalence were not. Cow-level mixed logistic regression models indicated no associations between any of the RAQ scores and presence of lameness or a hoof lesion. Lameness prevalence in Alberta remains high, indicative of a low adoption rate of mitigation strategies by producers. Improvement of the RAQ could allow for better prediction of lameness and lesions on farm and can be achieved through further risk factor analysis within the RAQ, which may result in removal or addition of questions as well as the adjustment of scores based on risk factors' strength of association with lameness and lesions.

2.2 Introduction

Lameness is one of the largest health problems in the dairy industry worldwide. It has a major economic impact, negatively affecting milk production (Green et al., 2002; Reader et al., 2011), longevity (Booth et al., 2004), and reproductive performance (Machado et al., 2010; Chapinal et al., 2013b). Additionally, due to its association with pain, lameness has a negative impact on welfare of dairy cattle (Whay and Shearer, 2017). Prevalence estimates in free stall-housed herds are consistently high on a global scale, spanning from China, Brazil and the UK estimated at 31, 43, and 32%, respectively (Chapinal et al., 2014a; Costa et al., 2018; Griffiths et al., 2018). In North America, lameness prevalence ranges from 15 to 55% (von Keyserlingk et al., 2012; Westin et al., 2016). A recent large Canadian study reported a prevalence of 21%, with 19% in the province of Alberta (Solano et al., 2015). Although lameness detection remains a subjective measure partly because of a variety of locomotion scoring systems, the Canadian Dairy Code of Practice considers a lameness prevalence of 10% to be an acceptable upper limit, further emphasizing the magnitude of this important health and welfare issue (National Farm Animal Care Council, 2009).

Risk factors for lameness are generally considered consistent with risk factors for hoof lesions, due to the reported 90% association between lameness and hoof lesions (Murray et al., 1996). However, this association has yet to be determined in North American free stall-housed dairy herds. Lesions can be either infectious or non-infectious, each type with their own unique risk factors that primarily arise from facility design of the barn and management of the herd. Factors reported to be associated with infectious lesions, predominantly digital dermatitis (DD), are internal and external biosecurity practices, footbath design and management, and environmental cleanliness (Relun et al., 2013; Cook, 2017; Oliveira et al., 2017). Reported factors for non-infectious lesions, including white line, sole ulcer and hemorrhage, include stall comfort and stocking density that both negatively impacting lying time, and trauma-related factors such as floor slipperiness and sharp turns (Barker et al., 2010; Solano et al., 2015; Solano et al., 2016b). In addition to these factors, it is important to consider cow-level factors that increase odds of a cow being lame, including higher age and low body condition (Solano et al., 2015). This knowledge can be helpful in monitoring cows most susceptible to lameness.

The repeated findings of the same risk factors for lameness indicates that adoption rate of known control and prevention strategies by producers remains low. A potential reason is drastic underestimation of lameness in their herds (Leach et al., 2010; Cutler et al., 2017). Another reason could be lack of producer awareness of these risk factors being present on their farm. In some studies, exposure of producers to an on-farm assessment aiming to identify farm-specific risk factors increased uptake of mitigation strategies (Chapinal et al., 2014b; Morabito et al., 2017).

As a more practical farm-specific approach towards control and prevention of lameness, a veterinarian-administered lameness risk assessment questionnaire (RAQ) was developed

(Alberta Milk, 2016). The RAQ is a score-based questionnaire that the veterinarian conducts with the producer with an aim of identifying farm-specific risk areas for infectious and non-infectious lesions to reduce lameness in the herd. However, accuracy of the RAQ in identifying risks for lameness and hoof lesions remains unknown.

The objectives of this study were, therefore, to: 1) determine the current prevalence of lameness, infectious, and non-infectious lesions in Alberta free stall herds; 2) determine the association between presence of a lesion and lameness; and 3) validate the RAQ by determining the association of RAQ scores with herd lameness and lesion prevalence.

2.3 Materials and Methods

All data collection protocols and questionnaires were approved by the University of Calgary Animal Care Committee (AC17-0163 & AC13-0082) and Research Ethics Board (REB17-1522).

2.3.1 Herd Selection

Selection of farms, to ensure representation of most dairy herds in Alberta, included a herd size of ≥ 40 lactating Holstein-Friesian cows housed in free stalls. In addition, eligible farms were enrolled in the CanWest DHI (Guelph, ON, Canada) milk recording program, had a professional hoof trimmer who was a member of the Western Canadian Certified Hoof Trimmers Association (**WCCHTA**), and were within reasonable driving distance (≤ 5 h) from the University of Calgary. Farms were excluded if they operated with automated milking systems or if the lactating herd had outdoor access for > 2 h/d.

Advertisement of the study was done through Alberta Milk (Edmonton, AB, Canada) for the recruitment of potential participants, where those who were interested (n = 11) could contact the graduate student (MV) for more information. In addition, farms that had already completed a RAQ with their veterinarian as part of Alberta Milk's Lameness Reduction Initiative (n = 88; Alberta Milk, 2016) and clients of participating WCCHTA hoof trimmers (n = 109) were contacted by telephone to determine interest in participation and whether eligibility criteria were met. Given these criteria and willingness to participate, a total of 65 herds were enrolled in the study.

For our 2nd objective, data were collected from 10 herds between November 2013 and June 2014 for a study where farm and cow selection were described (Solano et al., 2017a). Participating herds were visited twice, except for 2 herds that contributed data from one visit only. All cows within the herd were locomotion scored and determined lame if there was observation of a limp, consistent with a score ≥ 3 on the 5-point scale described below. A WCCHTA hoof trimmer visited the herd within 12-48 h after locomotion scoring to record and treat lesions. One herd was visited by the hoof trimmer 3 d after locomotion scoring due to a snow storm in the days before. Lesion and treatment data were digitally collected from the hoof trimmers.

2.3.2 Risk Assessment

The RAQ is composed of 9 sections: 1) general farm information, 2) farm biosecurity measures, 3) animal-based measures, 4) pregnant heifer facilities, 5) pregnant heifer management, 6) dry cow facilities, 7) dry cow management, 8) lactating cow facilities, and 9) lactating cow management. Within sections 2 to 9, multiple-choice questions were included

related to the farm's risk for infectious and/or non-infectious lesions or causes of lameness. Answers for each question are associated with a weighted risk score based on evidentiary literature and/or biological plausibility of the factor that is being assessed. The risk scores for each question sum to a total score for non-infectious and infectious causes of lameness in each section of the RAQ, with section scores adding to a total score for non-infectious and infectious causes of lameness. These 2 totals combined result in the total RAQ score. With this combined total RAQ score, it is important to note that some questions contribute the selected risk score to both the infectious and non-infectious causes of lameness, being counted twice.

During the farm visit, sections of the RAQ related to management and biosecurity measures were completed based on answers supplied by the producer or dairy manager during an interview. Remaining sections, related to facilities, were completed by the graduate student (MV) based on direct observation and required measurements. For questions within the lactating cow facilities section, the pen with the highest number of cows was selected for assessment. Pens containing animals that were most distant from their expectant calving dates were selected for assessment of pregnant heifer facilities and dry cow facilities sections. If these pens were inaccessible, those in the close-up pen were selected for assessment. Completion of the RAQ was done either before an afternoon milking time or after a morning milking time dependent on the preference of the producer or research team. The RAQ is available online (https://www.dairyresearch.ca/file.php?filename=/var/www/cdrplive/files/provincial/79/HH%20RAQ%20v160923.pdf).

2.3.3 Lameness Reduction Initiative Data

After launching of the LRI in 2016, the RAQ was conducted by trained veterinarians. By the fall of 2018, 137 assessments were completed by 25 veterinarians. A user guide was provided for applicable questions to ensure further consistency (https://www.dairyresearch.ca/file.php?filename=/var/www/cdrplive/files/provincial/78/HH%20RAQ%20User%20Guide%20v160923.pdf). Of the 65 herds enrolled in the current study, 33 had also completed a RAQ with their veterinarian. Observer reliability was assessed through the comparison of scores of 33 herds between the veterinarians (n=14) and graduate student. Four of the 33 herds had completed 2 RAQs with their veterinarian; therefore, only the most recent was kept for comparison with the study RAQ.

2.3.4 Lameness Assessment

The entire lactating herd was videotaped while exiting the milking parlor after milking in the most suitable location with a flat surface and enough space to allow for a minimum of 4 strides. In some herds, slatted floors were unavoidable, as well as floors that were more slippery than optimal. All lameness scoring was done at a later date by the same trained observer (MV), using the 5-point scale described in the Canadian Code of Practice for the Care and Handling of Dairy Cattle, adapted by the Animal Welfare Program at the University of British Columbia (Flower and Weary, 2006). A score of 1 and 2 were considered non-lame whereas scores 3, 4, and 5 were recorded as lame. Selection of cows assessed for lameness depended on the number of videos in which cows were walking for at least 4 strides with non-obstructed views of the head, back, and feet simultaneously and had identification linking to cow-level CanWest DHI information. Lameness scoring was then completed on all videos or systematically selected

videos (e.g. every second or third) to yield at least 40 cows scored, which on average, was 25% of the herd. Additional cow-based measures, including parity, DIM, and daily milk production were obtained from CanWest DHI (for the closest test date to date of study visit). Intra-observer reliability was assessed at the end of the study by re-scoring 10% of the videos, and a high level of agreement was determined with a weighted Kappa statistic ≥ 0.6 for lame versus non-lame.

2.3.5 Lesion Data

To account for a potential effect of seasonality on presence of hoof lesions (Sanders et al., 2009), 1 year of hoof trimming records was requested for each enrolled herd, retroactively from date of visit in 2018 to the same date of 2017. For 2 enrolled herds, the professional hoof trimmer did not use Hoof Supervisor™ (KS Dairy Consulting, Dresser, WI,) and was not a member of WCCHTA. However, due to the trimmer's participation in the Alberta Dairy Hoof Health Project (Solano et al., 2016a), a study that collected data on hoof lesions based on the records of professional hoof trimmers (including most WCCHTA members), an exception was made. For these 2 herds, paper copies of trim records were collected and digitalized. Variables included in the requested trim data included trimmer, cow ID, trim date, lesions, claws, and treatment. Lesion diagnosis and recording, as well as categorization of lesion types into non-infectious and infectious lesion outcomes at the cow level were consistent with ICAR classification (Egger-Danner et al., 2015).

2.3.6 Data Management and Statistical Analysis

To control for multiple records per cow, trim records were restricted to the 1 observation per unique cow closest to the study date visit.

All statistical analyses were performed using Stata 15.1 (StataCorp, 2015, College Station, TX) and $P < 0.05$ was considered significant. Herd-level characteristics were described using descriptive statistics to allow for comparison to provincial averages. To determine the cow-level association between presence of a lesion and lameness, odds ratios were calculated for selected types and categories of lesions. Associations between herd lameness prevalence, non-infectious lesion prevalence, infectious lesions prevalence and total RAQ score, non-infectious RAQ score, and infectious RAQ score, respectively, were estimated using Spearman's rank correlation. Observer bias was assessed by comparing correlations between RAQ scores and lameness prevalence for herds that had completion of the RAQ before videotaping of the lactating cows to herds that had completion of the RAQ after videotaping of the lactating cows.

For cow-level lesion outcome analyses, a herd being partially trimmed was defined as < 80% of the herd trimmed within a 15-d period, compared to whole herd trims with ≥ 80% of the herd trimmed within a 15-d interval (Solano et al., 2016a).

If 2 independent variables were highly correlated ($r \geq 0.60$), the variable with the strongest association with the outcome or the lowest number of missing observations was selected for analysis.

First, univariable analyses were performed to assess associations between the cow level outcome of interest, presence of lameness, non-infectious lesion, and infectious lesion, and each independent variable. Variables with a crude association with $P \leq 0.25$ were included in multivariable analyses. Variables in multivariable analyses with a $P < 0.10$ were included for backwards elimination, resulting in the final model where retained independent variables had an association with $P < 0.05$. A confounding variable was retained if its removal resulted in a ≥ 30% change in the coefficient estimates of other significant predictors. Interaction was tested

among significant predictors (2-way interactions). Farm was included as a random effect because of the significant variation in lameness and lesion prevalence between herds. For lesion outcome analyses, hoof trimmer and trimming routine (partial or whole) were kept in the model as a fixed effect due to potential inconsistencies between trimmers and partial trim herds having higher prevalence estimates than whole-trim herds because of selection bias introduced by producers who select cows for trimming based on clinical signs.

Upon launching of the RAQ as part of Alberta Milk's LRI, veterinarians in the province received training on conducting the assessment through on-farm workshops. For study herds that had also completed a RAQ with their veterinarian, median differences between the herds' study RAQ score and the veterinarian RAQ score were tested using the sign test. A $P < 0.05$ indicated the median difference between scores is not equal to zero and there is a significant difference between study and veterinarian RAQ scores. In addition, Lin's concordance correlation coefficient was computed for RAQ scores to determine level of agreement between veterinarians and the lead researcher.

2.4 Results

2.4.1 Lameness, lesion, and RAQ

Study farms had a mean herd size of 163 lactating cows, with mean daily and 305-d milk production of 36.9 and 11,085 kg, respectively (Table 2.1). Herd characteristics of this study represented the overall population of cows housed in free stalls in Alberta, with herd size and milk production being slightly higher, due to exclusion of small herds.

A total of 3,759 cows were assessed for lameness. Intra-observer agreement for locomotion scoring for lame versus not lame was 90% ($K_w \geq 0.64$). On average, 41% (17 – 78%) of the lactating herd was assessed for lameness. Herd-level lameness prevalence ranged from 2 to 56% with a median of 19.5% on the 65 farms (Figure 2.1). The 10% of herds (n=6) with the lowest lameness prevalence had a prevalence of < 8%, whereas in the 10% of herds with the highest lameness prevalence, > 38% of the cows were lame.

For the 63 participating herds, a total of 22,670 cow records were collected from the 8 hoof trimmers. Trim records became inaccessible for 2 herds due to a hard drive malfunction experienced by 1 trimmer as well as these herds not being able to find the trim records that the trimmer would have supplied them with after trim sessions. After restricting observations to the 1 most recent trim record per cow, 13,530 records were available for analysis. Of these records, 29.5% of cows had at least 1 hoof lesion, with 9% of those cows having > 1 hoof lesion (Table 2.2). Overall, herd-level infectious lesion prevalence, comprising 9.1% of DD, ranged from 0 to 49% with a median of 9.6% and non-infectious lesion prevalence ranged from 2 to 39% with a median of 14.7%. Most common non-infectious lesions were white line, sole ulcer, and sole hemorrhage with medians of 5.5, 4.9 and 2.2%, respectively. Mean estimates differed between partial-trim herds (18.1%; n=32) and whole-trim herds (12.9%; n=31) for non-infectious lesion prevalence ($P = 0.006$).

For lameness and lesion data collected between 2013 and 2014, 1680 cow records were collected from the herds' hoof trimmers (n=2) and were reduced to 1581 records when including cows with complete lameness observations. Distribution of lesion types and their association with lameness are summarized in Table 2.3. Overall, 93% of lame cows had the presence of a lesion and 21% of cows with a lesion were lame. Non-infectious lesions had a greater association

with lameness than infectious lesions, whereby cows with a non-infectious lesion were 3 times more likely to be lame, compared to cows with DD, the most common infectious lesion (OR = 1.7). Though there were fewer cases of sole ulcer and white line, the cows that presented these lesions had 5.7 and 6.3 times the odds of being lame, respectively.

Total RAQ score ranged from 50 to 114 points with a mean of 81 (±15) points out of a maximum of 241 points for 65 herds. Infectious RAQ score ranged from 27 to 64 points out of a maximum of 124 points, with a mean of 44 (±8) points, and non-infectious RAQ score ranged from 19 to 62 points out of a maximum of 117 points with a mean of 37 (±9) points for 63 herds. After careful consideration, section 3 was not included in the score count, due to these questions being related to national assessment participation and record keeping.

Within-herd lameness prevalence and total RAQ score ($r = 0.26$, $P < 0.05$) and within-herd non-infectious lesion prevalence and non-infectious RAQ score ($r = 0.45$, $P < 0.001$) were positively associated. However, there was no association between within-herd infectious lesion prevalence and infectious RAQ score ($r = 0.15$, $P > 0.05$). Herds where completion of the RAQ proceeded videotaping of the lactating cows (n = 21) had a stronger association between total RAQ score and lameness prevalence than herds where completion of the RAQ preceded videotaping of the lactating cows (n = 44). However, when total RAQ score was re-calculated after exclusion of subjective questions, the difference in strength of these associations, and therefore cannot be explained by observer bias.

2.4.1 Multi-level logistic models

Cow-level variables were only applicable in the final model with lame as the outcome. Confounding variables and 2-way interactions could not be retained in any model. In the final

model analyses, total RAQ score, infectious RAQ score, and non-infectious RAQ score had no association with the odds of a cow being lame, having an infectious lesion, and having a non-infectious lesion, respectively. The odds of a cow being lame increased with increasing parity, with third and fourth or higher lactation cows being 4 times and 7 times more often lame, respectively, compared to first-lactation cows (Table 2.4). Cows in a herd with > 165 lactating cows twice more frequently had an infectious lesion compared with cows in herds with < 110 cows (Table 2.5). In herds that were milked 3 times a day, cows were 37% less likely of having a non-infectious lesion than cows in herds milking 2 times a day (Table 2.6). The odds of a non-infectious lesion were 33% less in herds with a whole-herd trimming routine than in herds with a partial-herd trimming routine.

2.4.2 Inter-rater Agreement

Median total, infectious, and non-infectious RAQ scores were not different between veterinarian-administered assessments and assessments by the graduate student (MV) of this study (Table 2.7). Additionally, concordance coefficients, which reflect the level of agreement between veterinarian and graduate student assessment scores, were 0.71, 0.58, and 0.71 for total RAQ score, infectious RAQ score, and non-infectious RAQ score, respectively.

2.5 Discussion

The 65 free stall herds included in this study had a median lameness prevalence of 20%, consistent with reported estimates of 21% in the Maritime provinces of Canada (Jewell et al., 2019), and 19% last reported in Alberta (Solano et al., 2015). The latter comparison could be reflective of the continuing lack of prevention and control strategy uptake by producers in the

province. Our study estimate was higher than the 10% reported among 17 US states (Adams et al., 2017), 15% in Canada and Michigan (Westin et al., 2016), and 13% in Wisconsin (Cook et al., 2016). Lameness prevalence in this study was lower than 28, 31, and 55% in British Columbia, California, and northeastern United States, respectively (von Keyserlingk et al., 2012).

Differences in lameness prevalence can be due to housing systems, dairy characteristics, and methodology for locomotion scoring and lameness case definition. The study including 17 US states (Adams et al., 2017) comprised of herds with varying housing types, of which 32% combined had tiestall, pasture, and open lot systems, which can have a positive impact on lameness compared to free stall systems. Herd size has also been reported to have a negative association with prevalence (Chapinal et al., 2014a; Solano et al., 2015), with larger herds having lower prevalence, perhaps because of large operations having more staff to monitor, prevent, and control lameness and lesions. This can support the low prevalence estimate reported in Wisconsin as well as their selection for high-performance herds that could be less likely to have a lameness problem due to its negative association with milk production at the cow level (Reader et al., 2011), which could collectively apply to the herd level. Milking system can also be a factor in lameness prevalence, in which the lower estimate in Canada and Michigan could be attributable to herds having Automated Milking System (AMS), which may be due to the common producer perception of having more time to observe and detect lameness (Tse et al., 2017). However, more research is required on lameness prevalence in AMS systems, as another study had a larger estimate of 26% (King et al., 2016). The selection of cows for assessment can also impact lameness prevalence. In British Columbia, California and the northeastern United States, high production groups (within 120 DIM) were selected for assessment because they are

most susceptible to lameness (Green et al., 2002). In the current study, DIM was not a cow selection criterion and did not have an association with lameness; nor was the significance of average herd DIM relevant with OR = 1. Additionally, inter-and intra-observer variability was not assessed for the 76 evaluators in the study involving 17 US states. As gait scoring methods used are subjective, reliability of the scoring system by determining observer agreement is important.

Lesion prevalence estimates reported in this study were comparable to a prior study in Alberta (Solano et al., 2016a). After using the same methods to define herd trimming routine, it is of most interest to compare estimates for whole-trim herds, as they are most representative of lesion prevalence rather than partial-trim herds, due to selection bias introduced by the producer leading to overestimation of prevalence. Prevalence of infectious lesions was consistent with 16% previously reported (Solano et al., 2016a), whereas prevalence of non-infectious lesions reduced from 16 to 12%, although the significance of this decline was undetermined. Methodology was very similar between these 2 studies, with consistency in participant trimmers that diagnosed and recorded lesions using the same software. Therefore, lesion prevalence has remained relatively unchanged in Alberta after 6 years between data collection.

Lesions were reported in 93% of lame cows, consistent with previous studies (Murray et al., 1996; Somers and O'Grady, 2015). However, it is equally important to note that only 21% of cows presenting a lesion were lame. Sole ulcer and white line lesion had the highest association with lameness, where 54 and 58% of cows affected were lame, respectively. These results were consistent with the 54% (sole ulcer) and 61% (white line) reported in a recent Malaysian study (Sadiq et al., 2017). Although digital dermatitis was the most prevalence foot lesion, only 20% of cows affected with this lesion were lame. A plausible reason could be that certain stages of

digital dermatitis, such as the active M2 stage, are more painful that other more advanced (or chronic) stages that have a higher likelihood of causing clinical signs of lameness (Plummer and Krull, 2017). Another study reported pain thresholds to be significantly different between active, healing, and healed lesions, with active lesions being the most painful (Cutler et al., 2013). These reports including that of the current study, suggest that only examining lame cows to determine the prevalence of hoof lesions will result in an underestimation of DD prevalence.

Although total RAQ score and within-herd lameness prevalence, as well as non-infectious RAQ score and within-herd non-infectious lesion prevalence, were associated, these associations were relatively weak. This could be the result of an inaccuracy of the RAQ in identifying risk factors for lameness, highlighting the need of improvement in strengthening associations between risk factors and lameness and lesion prevalence or indicates the potential of important risk factors not being captured in the RAQ. The important question remains of which risk factors may have more of an impact on lameness than others, to then be followed by adjustment of the weights of the risk factor scores based on the answer to this question. This could include the importance of risk factor exposure during the first pregnancy, lactation, and dry periods of a cow's life, in prevention of lameness. In this study, the odds of lameness increased with parity, consistent with previous studies (Solano et al., 2015; Jewell et al., 2019). This association has been thought to be due to older cows being larger and heavier which exerts more pressure on the claw, being exposed to facility and management factors for a longer duration than primiparous cows, and having a higher likelihood of chronic lameness by means of poor recovery from lesions leading to their recurrence (Sarjokari et al., 2013). Parity is therefore a cow-level factor that has a large impact on lameness which further supports the importance of closely monitoring older cows in the herd.

Unlike previous studies (Solano et al., 2015; Adams et al., 2017), herd size was not a risk factor for lameness in the current study. A possible reason could be the different distribution of herd size among participants enrolled in these studies that resulted in an association with lameness prevalence. In the US, there is a much wider range in herd size, which the Adams et al. study reflected by their definitions of medium (100 to 499 cows) and large (≥ 500 cows) herds (2017). In contrast, the Canadian study included herds in Ontario and Quebec, in addition to Alberta, where average herd sizes are smaller and thus overall had more small herd participants than in the current study. A cow in a herd with ≥ 165 lactating cows, however, did have 2 times the odds of having an infectious lesion compared to cows in a herd of < 100 cows. This association could be due to larger herds having an increased likelihood of being open herds, in which the purchase of animals from elsewhere comes with increased risk of introducing infectious lesions (Oliveira et al., 2017). The weak association between prevalence of infectious lesions and lameness in the current study could explain why herd size is a risk factor for infectious lesions and not lameness.

In the current study, milking 3 times a day was negatively associated with the presence of a non-infectious lesion, when compared to milking 3 times a day. This result is interesting, given the additional standing time in the holding pen that would exert more pressure on the claw; however, this could be counteracted by milking fewer cows in several groups. Though few studies have investigated the effect of milking frequency on hoof health, one study determined that cows being milked three times a day had a 36% higher probability of lameness than that of cows milked twice daily (Caixeta and Bicalho, 2011). However, this study had the limitation of only including 1 herd, divided into 2 groups to test these milking frequencies. Perhaps for the herds in the current study, the additional milking time allows for more monitoring and detection

of problem cows with non-infectious lesions that may be presenting signs of lameness. More research would be beneficial in better understanding the association between milking frequency and lameness.

Herds with a trimming routine in which the whole herd is trimmed within 15 d, 2 or 3 times a year, had a lower prevalence of non-infectious lesions. This was also reflected by the significant difference in estimates between partial-trim and whole-trim for non-infectious lesions only. Selection bias in partial-trim herds can explain these results whereby producers select a proportion of cows to present to the trimmer including problem cows that are visibly lame, causing an overestimation of prevalence (Solano et al., 2016a). The stronger association between non-infectious lesions and lameness reported in the current study may explain why trimming routine had an impact on these lesions and not infectious lesions. Additionally, infectious lesions can be treated by farm staff with more ease than the corrective trimming required for treatment of non-infectious lesions.

In the RAQ validation of inter-rater agreement, there was no difference in scores for the 33 herds that had completed an RAQ by both their herd veterinarian and lead researcher of this study. Therefore, the reasoning for the RAQ inaccuracy in predicting lameness and lesion prevalence can be due to the question content and score weights of the risk factors, rather than inconsistency between evaluators.

2.6 Conclusions

Lameness prevalence remains 20% in Alberta free stall herds and has not changed since the last study in 2012. The associations between RAQ scores and herd lameness and lesion prevalence were non-existent or weak. There was no difference in scores between observers,

which indicates that improvement in the accuracy of the RAQ can be done by further identifying the associations between the risk factors within the questionnaire and lameness and lesion prevalence, followed by adjustment of risk score weights. The RAQ is still viewed as a helpful and practical approach in the facilitation of discussion between producers and their advisors on lameness reduction and control in their herds.

Table 2.1. Descriptive characteristics (mean ± SD) of 65 study dairy farms and the average free stall dairy farm in Alberta.

Variable	Average Alberta free stall farm[1]	Study farms (n = 65)
Herd size (no. lactating cows)	140	163 ± 77
Daily milk yield (kg)	35.2	36.9 ± 3.6
Parity	2.2	2.2 ± 0.2
305-d milk yield (kg)	10,643	11,085 ± 899
DIM	172	170 ± 20

[1] Data from 2018. Source: CanWest DHI (Guelph, ON, Canada).

Table 2.2. Herd- and cow-level prevalence (%) of hoof lesions in 63 herds and 13,530 dairy cows as recorded by 8 trimmers in Alberta, Canada.

	Partial-trim (n = 32)		Whole-trim (n = 31)		Overall (n = 63)	
Lesion	Cow prevalence	Median within-herd prevalence	Cow prevalence	Median within-herd prevalence	Cow prevalence	Median within-herd prevalence
Any lesion	32.6	30.7 (2.6 – 65.4)[1]	26.3	22.1 (4.3 – 61.1)[1]	29.5	27.6 (2.6 – 65.4)[1]
Multiple lesions	10.3	8.6 (0.0 – 30.1)	8.1	5.7 (1.0 – 19.6)	9.3	8.3 (0.0 – 30.1)
Infectious	15.6	10.5 (0.0 – 49.0)	14.5	7.7 (0.0 – 47.7)	15.1	9.6 (0.0 – 49.0)
Digital dermatitis	14.6	10.1 (0.0 – 49.0)	13.6	7.5 (0.0 – 43.3)	14.1	9.1 (0.0 – 49.0)
Non-infectious	18.3	17.0 (2.6 – 38.8)	12.4	11.7 (2.4 – 25.6)	15.4	14.7 (2.4 – 38.8)
Sole ulcer	6.4	5.6 (1.8 – 23.0)	4.5	4.2 (0.5 – 11.4)	5.5	4.9 (0.5 – 23.0)
White line	8.0	7.4 (0.0 –16.5)	4.5	3.4 (1.2 – 16.1)	6.3	5.5 (0.0 – 16.5)
Sole hemorrhage	3.0	1.5 (0.0 – 12.3)	3.5	2.6 (0.0 – 14.9)	3.2	2.3 (0.0 – 14.9)

[1]Minimum to maximum.

Table 2.3. Distribution and association between lesion and lameness cases as recorded for 1581 dairy cows on 10 farms in Alberta, Canada.

Lesion type	Lameness absent	Lameness present	Percent lame	Percent of lameness cases (n=303)	Odds of lameness (95% CI)
Any lesion	1076	283	20.8	93.4	2.7 (1.7 – 4.3)
Infectious lesion	1018	260	20.3	85.8	1.5 (1.1 – 2.2)
Digital dermatitis	912	245	21.2	80.9	1.7 (1.2 – 2.3)
Non-infectious lesion	433	186	30.0	61.4	3.1 (2.4 – 4.0)
Sole ulcer	39	46	54.1	15.2	5.7 (3.6 – 8.9)
White line lesion	21	29	58.0	9.6	6.3 (3.6 – 11.3)

Table 2.4. Final mixed-effects logistic regression model for lameness with cow- and herd-level factors for 65 dairy herds in Alberta, Canada (n = 3,641).

Variable	Coefficient	Odds Ratio	95% CI	*P*-value
Total RAQ score	0.01	1.01	1.00 – 1.02	0.107
DIM	0.00	1.00	1.00 – 1.00	0.011
Parity				
1	Ref			
2	0.43	1.54	1.20 – 1.98	0.001
3	1.41	4.08	3.16 – 5.27	< 0.001
≥ 4	1.98	7.24	5.64 – 9.28	< 0.001
Herd avg DIM	0.01	1.01	1.00 – 1.02	0.005

Table 2.5. Final mixed-effects logistic regression model for infectious lesions with herd-level factors for 63 dairy herds in Alberta, Canada (n = 13,530).

Variable	Coefficient	Odds Ratio	95% CI	*P*-value
Infectious RAQ score	0.01	1.01	0.98 – 1.05	0.485
Herd avg DIM	0.03	1.03	1.01 – 1.04	< 0.001
Herd size[1]				
< 110	Ref			
110 – 164	0.57	1.76	0.88 – 3.50	0.107
≥ 165	0.80	2.21	1.02 – 4.80	0.044

[1]Number of lactating cows.

Table 2.6. Final mixed-effects logistic regression model for non-infectious lesions with herd-level factors for 63 dairy herds in Alberta, Canada (n = 13,530).

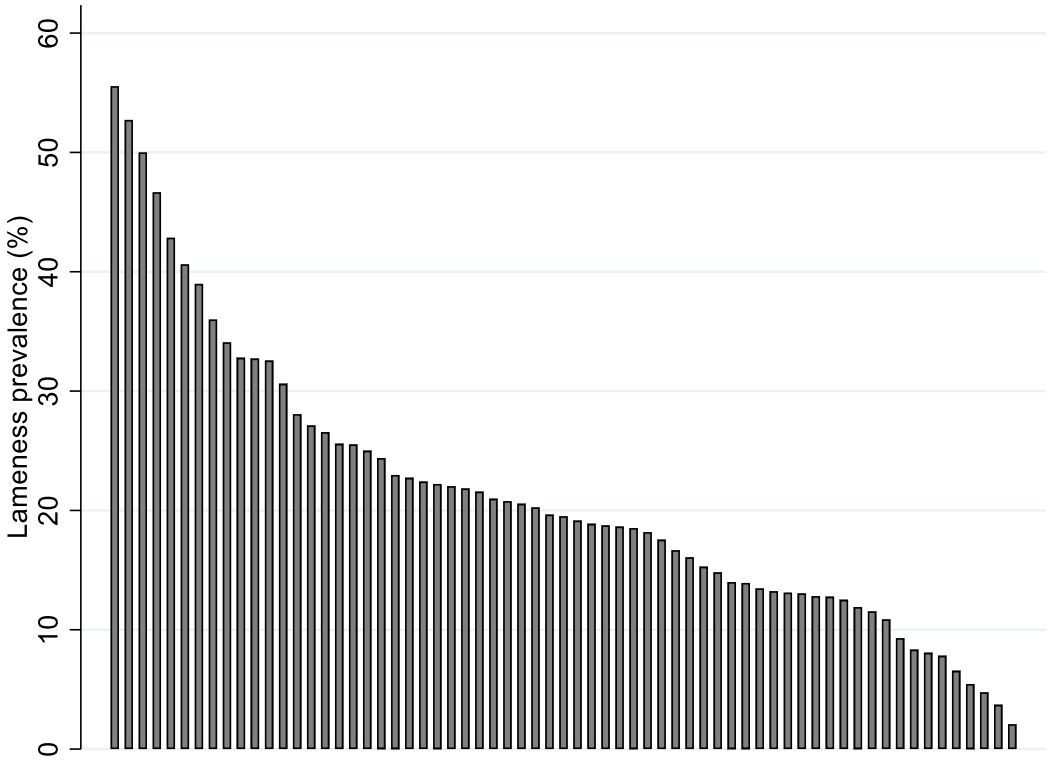
Variable	Coefficient	Odds Ratio	95% CI	*P*-value
Non-infectious RAQ score	0.02	1.02	1.00 – 1.03	0.027
Milking frequency				
2 times/day	Ref			
3 times/day	-0.46	0.63	0.47 – 0.84	0.002
Trimming routine[1]				
Partial	Ref			
Whole	-0.41	0.67	0.51 – 0.88	0.004

[1]Partial = < 80% of lactating and dry cows trimmed within a 15-d interval; Whole = ≥ 80%.

Table 2.7. Score comparison and agreement between the graduate student and veterinarians that had completed a RAQ on 33 study participant farms.

Scores	Study median (min – max)	Veterinarian median (min – max)	Score differential median (min – max)	Sign test *P*-value	Concordance correlation coef.
Total RAQ	81 (56 – 112)	80 (53 – 126)	8 (0 – 26)	0.281	0.705
Infectious RAQ	43 (27 – 56)	45 (24 – 68)	5 (0 – 20)	0.215	0.582
Non-infectious RAQ	36 (24 – 62)	36 (20 – 58)	4 (0 – 16)	0.720	0.714
Section 2	12 (6 – 18)	12 (4 – 19)	3 (0 – 6)	0.210	0.743
Section 4	3 (0 – 16)	5 (0 – 13)	2 (0 – 9)	0.136	0.495
Section 5	9 (2 – 22)	11 (0 – 21)	3 (0 – 12)	0.856	0.647
Section 6	5 (0 – 19)	5 (1 – 23)	3 (0 – 18)	0.362	0.424
Section 7	5 (0 – 11)	7 (0 – 16)	2 (0 – 8)	0.424	0.177
Section 8	27 (17 – 40)	24 (14 – 40)	5 (0 – 14)	0.110	0.364
Section 9	12 (6 – 19)	11 (7 – 29)	2 (0 – 11)	0.572	0.465

Figure 2.1. Distribution of within-herd lameness prevalence for 65 dairy herds in Alberta. Each bar represents a herd.



Chapter 3: OPTIMIZING A LAMENESS RISK ASSESSMENT TO IMPROVE IDENTIFICATION OF RISK FOR LAMENESS AND FOOT LESIONS ON DAIRY FARMS IN ALBERTA, CANADA

3.1 Abstract

Lameness is a major herd health issue globally and negatively impacts the welfare of dairy cattle. A score-based risk assessment questionnaire (RAQ) was developed in Alberta as part of a lameness control program to identify farm-specific risk of lameness and hoof lesions, followed by directed intervention strategies. However, its accuracy in risk identification is poor and requires improvement. The objectives of this study were to: 1) determine risk factors in the RAQ that are associated with lameness and lesion prevalence and; 2) to optimize the RAQ after adjustment of risk score weights for associated risk factors and determining the association between total RAQ scores and herd-lameness and -lesion prevalence. From March to October 2018, 65 herds were visited once, and data collected included a completed RAQ, hoof trimming records for lesion assessment, and video footage of the lactating herd for lameness assessment. Univariate and multivariate analyses were conducted to determine associated risk factors for three outcomes: lameness, infectious lesions, and non-infectious lesions. Of the 58 management and facility related risk factors in the RAQ analyzed, 21 were positively associated with the three outcomes. However, only 12 risk factors qualified for an increase in risk score weights based on the resulting odds ratios. After score adjustments of these risk factors, the association, measured with Spearman's rho, for total RAQ score and herd lameness prevalence increased from 0.26 to 0.32 ($P < 0.01$), total infectious RAQ score and herd infectious lesion prevalence increased from 0.15 to 0.24 ($P < 0.1$), and total non-infectious RAQ score and herd non-infectious lesion

prevalence increased from 0.45 to 0.54 ($P < 0.001$). In conclusion, the strength of association between total RAQ scores, as a measure of overall farm-specific risk, and herd-lameness prevalence remains weak and will need further improvement in its accuracy. However, the associated risk factors determined in this study can support producers and advisors by being prioritized in directed intervention strategies for lameness control and mitigation.

3.2 Introduction

Lameness in the dairy industry continues to be a herd health problem on a global scale with consequential impact on milk production (Green et al., 2002; Reader et al., 2011), longevity (Booth et al., 2004), and reproductive performance (Machado et al., 2010; Chapinal et al., 2013b). The welfare of dairy cattle is also negatively affected due to the association between lameness and pain (Whay and Shearer, 2017). Among North American free stall barns, mean lameness prevalence ranges from 15% to 55% (von Keyserlingk et al., 2012; Westin et al., 2016). The province of Alberta has a reported mean prevalence of 19%, as part of a larger Canadian study (Solano et al., 2015). These estimates are much higher than the 10% that the Canadian Dairy Code of Practice considers to be an acceptable limit, further emphasizing the magnitude of this health and welfare issue (National Farm Animal Care Council, 2009), which has led to mandatory assessments of lameness in Canada as part of Dairy Farmers of Canada's proAction program (Dairy Farmers of Canada, 2015).

The lack of implementation of successful strategies by producers towards the control and reduction of lameness is apparent with consistent high prevalence in Alberta (van Huyssteen et al., 2019). In the mitigation of other herd health issues, such as Johne's disease, which rely heavily on management changes made by producers, there has been some success with the

development of voluntary control programs that involve risk assessments followed by management plans for corrective action (Sorge et al., 2010; Wolf et al., 2014). These control programs can be viewed as a hazard analysis critical control point (HACCP) approach to reducing the issue. This system is regularly used in the food production and manufacturing processes to adhere to food safety and has a focus of identifying the critical control points (CCPs) during this process and implementing corrective action where needed to prevent arising problems (Majewski, 1992).

The HACCP approach has been increasingly utilized for addressing health and welfare issues, including mastitis and lameness control on dairy farms (Bell et al., 2009; Beekhuis-Gibbon et al., 2011a). Using this approach towards the mitigation of the high lameness prevalence in Alberta, a veterinarian-administered lameness risk assessment questionnaire (RAQ) was developed and launched in 2016 as part of Alberta Milk's voluntary control program, the Lameness Reduction Initiative. The RAQ focuses on identifying farm-specific management and facility areas that increase the risk of infectious and non-infectious hoof lesions, as their presence is reported in most lameness cases (Murray et al., 1996; van Huyssteen et al., 2019). Questions are related to risk factors for these types of lesions which have previously been identified in several scientific studies. The answers provided for each question are associated with an ordinal score, where higher scores are associated with increased risk of lesions and lameness, with an overall expectation that herds with higher cumulative scores have higher lesion and lameness prevalence. This positive association between RAQ scores and prevalence has been recently determined to be weak with low predictability of prevalence based on risk scores from the on-farm assessment. To be a functional tool, the accuracy of the RAQ needs to be improved to better identify the critical control points of lameness by determining its strengths

to allow prioritization of management practices and facility design changes that would have the highest impact on lameness, followed by adjustment of the question makeup and scoring strategy of the assessment.

Therefore, the objectives of this study are to (1) determine the risk factors likely to be critical control points in the RAQ that have the strongest association with the prevalence of lameness, infectious lesions, and non-infectious lesions, and (2) optimize the RAQ after the quantification of risk factors through the adjustment of risk score weights. Previous lameness events are becoming of growing importance as a large contributing risk factor to future lameness events (Randall et al., 2018). This is speculated to be the case for cows that become lame due to common non-infectious lesions that, if not treated quickly, can lead to the development of additional bone on the distal phalanx, increasing a cow's susceptibility to future lesions and lameness (Newsome et al., 2016).Therefore, we also investigated the association between lameness prevalence and the prevalence of cows with multiple occurrences of these lesions, using the longitudinal lesion data collected of one year.

3.3 Materials and Methods

All protocols and questionnaires were approved by the University of Calgary Animal Care Committee (AC17-0163 & AC13-0082) and Research Ethics Board (REB17-1522).

3.3.1 Herd Selection and Data Collection

Results for the current study are based on data collected for a previous cross-sectional study (van Huyssteen et al., 2019) that consisted of 65 voluntary participant herds. Data were

collected between March and October of 2018 by the lead graduate student (MV) and assisting students. Briefly, the study included free-stall herds with at least 40 lactating Holstein-Friesian cows and little to no outdoor access. Additional eligibility criteria consisted of CanWest DHI enrollment, having a professional hoof trimmer that is a member of the Western Canadian Certified Hoof Trimmers Association (WCCHTA), and a parlor milking system (no automated milking systems). Each enrolled herd was visited once in which a visit consisted of: (1) completion of a RAQ, (2) videotaping the entire lactating herd during milking as they exited the milking parlor for later assessment of lameness prevalence, and (3) attaining permission to collect a year worth of hoof trimming records from the herd's WCCHTA hoof trimmer for later assessment of lesion prevalence. The process of lameness and lesion assessment has been described in detail (van Huyssteen et al., 2019).

The RAQ consisted of 9 sections: (1) general farm information, (2) farm biosecurity measures, (3) animal-based measures, (4) facilities for pregnant heifers, (5) management practices for pregnant heifers, (6) facilities for dry cows, (7) management practices for dry cows, (8) facilities for lactating cows, and (9) management practices for lactating cows. Section 1 had 10 questions related to herd characteristics and section 3 had 7 questions related to the herd's results in the national mandatory proAction Animal Care Assessment and hoof trimming record keeping. The remaining 70 questions within sections 2 and 4 to 9 were the risk factors inferred from various evidentiary literature. Questions in each section supplied 2 to 4 optional answers where 1 was chosen that best described the participant herd. A question aimed at the identification of risk for infectious and/or non-infectious lesion development, with every question assumed as identification of risk for lameness. Management related questions were answered by the producers and facility related questions were answered by the graduate student

based on observation and necessary measurements. RAQ questions and herd responses stratified by lameness prevalence are listed in Appendix 1.

3.3.2 Data Management and Statistical Analyses

Statistical analyses were performed using Stata 15.1 (Statacorp, College Station, TX). Potential predictors being analyzed were the questions in the RAQ, as related to risk factors, excluding those in sections 1 and 3. The outcomes of interest were cow- and herd-level lameness and lesion prevalence.

With the present data set comprising many independent variables (RAQ questions), two methods were used for data analysis in the identification of critical questions that will be utilized to optimize the RAQ: (1) univariate analysis for the assessment of crude associations between the various questions and the outcomes; and (2) multivariate analysis to correct for multicollinearity between questions, with the application of a factor analysis (Dohoo et al., 1997). Additional variables included for multivariate analyses were both cow-level (parity, DIM, milk production), for the lameness outcome explicitly, and herd-level variables for all outcomes (herd size, average milk production, milking frequency among others).

Univariate Analysis. Logistic regression models were constructed with 3 different cow-level outcomes; (1) presence of lameness, (2) presence of an infectious lesion, and (3) presence of a non-infectious lesion. Discrete models were built for each question presented in the RAQ, included as categorical predictors where a P-value < 0.05 for at least one of the categories was determined significant. Only questions that had responses from all 65 herds were considered for analysis due to their increased interest while also maximizing power to determine associations.

Multivariate Analysis. With high likelihood of multicollinearity among many independent variables, exploratory factor analysis was investigated as a method to summarize correlations using a variable matrix while avoiding the loss of information. Before proceeding with multivariate analysis, some variables had response categories combined if a category contained ≤ 2 herds and combining was biologically relevant. The ordinal nature of the categories from low to high risk was prioritized, however, some variables with a reference category that contained ≤ 5 herds were combined with the next category when relevant or the reference category was changed to the most common response. In the case of a binary variable, it was excluded from analyses if one of the two categories contained < 5 herds.

As a prerequisite for factor analysis, suitability of the dataset was assessed by measurement of sampling adequacy with the Kaiser-Meyer-Olkin (KMO) method. Medium fit of the data was determined with an overall KMO > 0.70. However, a value greater than this arbitrary threshold was not achieved, therefore, factor analysis was deemed not to be a suitable method for the entire dataset. Instead, an independent variable matrix was created to determine multicollinearity among questions that had a response from all participants with an arbitrary r > |0.6| for two questions to be considered multicollinear. Questions determined to be related to other questions were then analyzed with factor analysis to confirm common groups as identified by the independent variable matrix. Retained factors had an Eigenvalue ≥ 1 and factor loadings > |0.5| were used to describe the factors after varimax rotation. Crude associations of predicted factor scores and all other independent variables with the three outcomes were determined using univariate mixed-effects logistic regression models. Variables with P < 0.25 were then included in multivariate analysis and were removed one at a time based on the largest p-value until all

remaining variables were significantly associated with the outcome ($P < 0.10$). Variables that had been removed were then added one at a time to confirm its association with the outcome, conditional on the remaining terms in the model. A confounding variable was determined and retained if its removal from the model resulted in a ≥ 30% change in the coefficient of a significant variable. The final model consisted of variables that had an association with the outcome at the 10% significance level. Biologically plausible two-way interactions among significant variables were assessed for effect modification. For all outcomes, farm was in the model as a random effect to adjust for the variation in lameness and lesion prevalence between herds. Additionally, for lesion outcomes, hoof trimmer and trimming routine was in the model as a fixed effect, as has been previously described in more detail (van Huyssteen et al., 2019).

Adjusting RAQ Scores. Results from the univariate and multivariate analyses were used to adjust the weight of the risk scores for significant questions based on odds ratios as an indicator of magnitude. Original risk scores of categories within significant questions and were adjusted accordingly based on the resulting odds ratio, rounded to the nearest whole number for the point value of the category. RAQ scores were then recalculated with the adjusted scores, and Spearman's correlation was used to determine strength of the associations between total RAQ score, infectious RAQ score, and non-infectious RAQ score with lameness, infectious, and non-infectious lesion prevalence.

Previous Lesion Events. To evaluate the impact of recurring common non-infectious lesions (sole ulcer, white line, sole hemorrhage, and toe ulcer) on lameness, this association is of most interest for the herds that have a partial trimming routine more frequently throughout the

year. Pearson's correlation was used to determine the association between herd-lameness prevalence and the prevalence of cows with ≥3 or ≥ 4 recorded non-infectious lesions.

3.4 Results

All 65 participants had complete RAQ data and a total of 3,759 cows were assessed for lameness. Two herds had incomplete lesion records due to difficulty downloading data from one of the 8 hoof trimmers. Of the 63 herds that had complete lesion data, a total of 13,530 records were used for analysis. Overall, 12 questions were excluded from all analyses (Q2.2, Q4.1a, Q6.1a-f, Q8.1, Q8.1a-b, and Q9.4) due to either < 100% herd response rate, or all herds contributed to one response category and allowed no comparison to be made.

3.4.1 Univariate Analysis

Lameness. Of the remaining 58 questions within the RAQ analyzed in univariate logistic regression, 14 had a significant association with lameness, including 8 related to facility design in the pregnant heifer, dry cow, and lactating cow facilities; and 6 related to management practices for pregnant heifers and lactating cows only (Table 3.1).

Infectious lesion. Of the remaining 58 questions within the RAQ, 40 were based on risk of infectious lesions and were analyzed in univariate logistic regression. Of these 40 questions, 6 were significantly associated with presence of an infectious lesion, including 2 facility factors for pregnant heifers only; and 4 management practices for pregnant heifers and lactating cows only (Table 3.2).

Non-infectious lesion. Of the remaining 58 questions within the RAQ, 37 were based on risk of non-infectious lesions and were analyzed in univariate logistic regression. Of these 37

questions, 6 were significantly associated with presence of a non-infectious lesion, including 4 facility factors for dry cows and lactating cows only; and 2 management practices for pregnant heifers and dry cows only (Table 3.3).

3.4.2 Multivariate Analysis

Binary questions excluded from multivariate analysis include Q2.5, Q2.6, Q2.7, Q8.1e, Q84, Q9.1, and Q9.4c for categories containing < 5 herds. Other questions excluded include Q4.2 and Q7.5, due to multicollinearity (r = 1.0) with Q4.1 and Q5.6, respectively. Reference categories were changed for Q8.1c and Q9.3.

Factor analysis for lameness outcome. Determined factors were based on the non-parametric correlation matrix that contained 3,759 observations from 65 herds. Of the 53 questions, 17 were related to ≥ 1 other question(s) (r > |0.6|). Among the 17 related questions, 5 groups were identified and confirmed through factor analysis as 5 factors with an Eigenvalue > 1. All factors had factor loadings of associated questions > |0.6|. Factor 1 was associated with dry cow facility type (Q6.1), bedding depth (Q6.2), type of floor surface (Q6.4), and dry cow footbath management (Q7.4). Factor 2 was associated with pregnant heifer bedding wetness (Q4.3), pregnant heifer leg cleanliness (Q4.5), dry cow bedding wetness (Q6.3), and dry cow leg cleanliness (Q6.8). Factor 3 was associated with pregnant heifer facility type (Q4.1), bedding depth (Q4.2), floor slipperiness (Q4.4) and dry cow floor slipperiness (Q6.6). Factor 4 was associated with time to treatment after a cow is identified as lame or when a lesion is found for pregnant heifers (Q5.4), dry cows (Q7.3), and lactating cows (Q9.2). Factor 5 was associated with percentage of pregnant heifers that have hooves examined before calving (Q5.1), how often pregnant heifers' hooves are examined (Q5.2), and how producers decide when to examine

pregnant heifers' hooves (Q5.3). After univariate analyses, factor 1 (P = 0.037), factor 3 (P = 0.111), and factor 4 (P = 0.093) qualified for inclusion in the lameness multivariate model.

Factor analysis for infectious and non-infectious lesion outcome. Determined factors were based on the non-parametric correlation matrix that contained 13,530 observations from 63 herds. Of the 53 questions, 14 were related to ≥ 1 other question(s) (r > |0.6|). Among the 14 related questions, 4 groups were identified and confirmed through factor analysis as 4 factors with an Eigenvalue > 1. All factors had factor loadings of associated questions > |0.5|. Factor 1 was associated with pregnant heifer facility type (Q4.1) and floor slipperiness (Q4.4); dry cow facility type (Q6.1), bedding depth (Q6.2), and type of floor surface (Q6.4); and dry cow footbath management (Q7.4). Factor 2 was associated with time to treatment after a cow is identified as lame or when a lesion is found for pregnant heifers (Q5.4), dry cows (Q7.3), and lactating cows (Q9.2). Factor 3 was associated with percentage of pregnant heifers that have hooves examined before calving (Q5.1), how often pregnant heifers' hooves are examined (Q5.2), and how producers decide when to examine pregnant heifers' hooves (Q5.3). Factor 4 was associated with pregnant heifer bedding wetness (Q4.3) and leg cleanliness (Q4.5). After univariate analyses, factor 1 (P = 0.216) qualified for inclusion in the infectious lesion multivariate model. Factor 1 (P = 0.174), and factor 3 (P = 0.137) qualified for inclusion in the non-infectious multivariate model.

Lameness multivariate model. The final model for lameness included 6 questions from the RAQ. Cows in a herd with a daily required standing time of 1 – 2 hours are 1.9 times more likely to be lame than cows in a herd with less than an hour of standing time (P < 0.001). In herds with a stocking density of 1 – 1.1 cows per stall, cows were 1.5 times more likely to be lame than cows in a herd with a stocking density of < 1 cow per stall (P = 0.05). Identified risk

factors related to footbath management include a liquid depth of < 10 cm compared to >10 cm (OR = 1.4; *P* = 0.041) and producers that sometimes or often depart from their footbath schedule compared to producers that never depart from their footbath schedule (OR = 1.9; *P* = 0.011). Lactating cow leg cleanliness was also associated with the odds of a cow being lame with a total score of 11-20 after sampling 10 cows had an odds ratio of 1.6 compared to a total score of ≤ 10. In herds that had a concrete floor surface on the animal-side of the dry cow feeders, cows were 1.6 times more likely to be lame than cows in herds with stone-free ground (*P* = 0.042) (Table 3.4).

Infectious lesion multivariate model. The final model for infectious lesions included 4 questions from the RAQ. Cows in a herd where the producer sometimes or often departs from their footbath schedule were 3.6 times more likely to have an infectious lesion than cows in herds where the footbath schedule is never departed from (*P* = 0.004). Herds with a lactating cow stocking density of > 1.2 cows/stall resulted in an odds ratio of 0.2 compared to herds with < 1 cow/stall. (*P* = 0.009). Cows in a herd with a required standing time of 1 – 2 hours were 43% less likely to have an infectious lesion than cows in herds with less than 1 hour of standing time. Lastly, herds that never examined the dry cows for hoof lesions resulted in an odds ratio of 0.14 compared to herds that would examine the dry cows when limping or at a scheduled exam (*P* = 0.093; Table 3.5).

Non-infectious lesion multivariate model. The final model for non-infectious lesions included 5 questions from the RAQ. A milking frequency of 3 times/day compared to 2 times/day resulted in an odds ratio of 0.65 (*P* = 0.002). Cows in a herd that have a whole-herd trimming routine are 37% less likely to have a non-infectious lesion than cows in herds with a partial-herd trimming routine. Cows in a herd with a moderately to very slippery floor surface in

the dry cow facility were 1.7 times more likely to be lame than those in a herd with a floor surface that is not slippery ($P = 0.029$). A feeder space of 46 – 60 cm/cow resulted in an odds ratio of 0.45 compared to > 60 cm/cow ($P = 0.008$). Cows in a herd with a stocking density of > 1.2 lactating cows/stall were 1.7 times more likely to be lame than cows in a herd with < 1 cows/stall. A concrete surface in the lactating cow feed alley resulted in cows being 56% less likely to be lame than a rubber surface ($P < 0.001$). Cows in a herd with a moderately slippery floor surface in the lactating cow facility were 1.3 times more likely to be lame than those in a herd with a non-slippery surface (Table 3.6).

3.4.3 Adjusting RAQ Scores

Based on significant question categories and their odds ratios in both univariate and multivariate models for lameness, infectious and non-infectious lesion outcomes, 12 questions were altered for increased weights and 18 questions were altered for decreased weights (Table 3.7). The Spearman's rho for lameness prevalence and total RAQ score increased from 0.26 to 0.33 ($P = 0.007$). For infectious lesion prevalence and infectious RAQ score, the Spearman's rho increased from 0.15 to 0.26 ($P = 0.040$). The Spearman's rho for non-infectious lesion prevalence and non-infectious RAQ score increased from 0.45 to 0.54 ($P < 0.001$). Scatterplots of these associations are presented in Appendix 2.

3.4.4 Previous non-infectious lesion events

Overall, 30 herds had the presence of 1 or more cows with ≥ 3 painful non-infectious lesions recorded that was positively associated with herd lameness prevalence ($r = 0.55$, $P = 0.002$). Of these 30 herds, 21 had a partial trimming routine and that was associated

with lameness prevalence (r = 0.59, $P = 0.005$). Sixteen partial trim herds had a prevalence of cows with ≥ 4 lesions recorded and had a strong association with herd lameness prevalence (r = 0.64, $P = 0.008$).

3.5 Discussion

Identified risk factors in the RAQ, based on both univariate and multivariate analyses, included 9 questions related to management practices and 12 questions related to facility design. Changes were made to the risk scores of answer categories based on them having higher odds of ≥ 1 of the three outcomes (lameness, infectious, and non-infectious lesions). This resulted in 12 questions to qualify for risk score adjustment to their supplied answer categories. After adjustment to these questions, the resulting associations between total RAQ scores and within-herd lameness remain to lack the desired strength in identifying overall risk for lameness and lesions, and thus, and their critical control points. Of additional interest, the association between prevalence of cows with ≥ 3 common non-infectious lesions and prevalence of lameness is strong and suggests the recurrence of these lesions is another important cow-level factor contributing to lameness in the herd. This factor may also be a useful addition to the RAQ as a herd-level measure with its potential in being a potential critical control point for lameness control.

A risk factor associated with all three outcomes, based on univariate analyses, was the percentage of pregnant heifers that have their hooves examined or trimmed before calving, where the odds of lameness, infectious lesions, and non-infectious lesions were higher for the herds that examined 50 – 80% of their pregnant heifers compared to the herds that examine > 80%. The odds were highest for infectious lesions, which can support the results of a previous study that

determined prevalence of DD among heifers, and thus early intervention can help minimize the spread of DD upon entering the lactating herd (Jacobs et al., 2017). Solano et al. also reported DD prevalence to be highest in first lactation cows (2016). Therefore, the current study further supports that examining pregnant heifers before calving is an important management practice for the control and mitigation of not only infectious lesions, but also non-infectious lesions and lameness.

Higher stocking density in the lactating cow facility was associated with increased odds of lameness and non-infectious lesions. Stocking density is viewed as a risk factor for lameness in the RAQ due to its association with standing time (increased claw loading) and lying time (decreased claw loading). A previous study reported stocking density to reduce lying time by 1.7 h/d, yet this seemingly small difference was the result of increasing density from 1 cow/stall to 1.5 cows/stall (Fregonesi et al., 2007). Yet in a Canadian study, stocking density of > 100% was not associated with either lameness or reduced lying time (Solano et al., 2015, Solano et al., 2016b). While lying times seem to be negatively impacted at much higher stocking densities, the current study was able to detect risk of both lameness and non-infectious lesions at stocking densities between 1 – 1.1 cows/stall and > 1.2 cows/stall, respectively. However, only 6% of herds had a stocking density of > 1.2 cows/stall, indicating that overstocking was not a common practice, and all remaining herds were within an acceptable stocking density as stated by the Canadian Dairy Code of Practice (National Farm Animal Care Council, 2009). Nevertheless, overstocking at any level should be cautioned given the additional evidence of risk presented by the present study.

A footbath frequency of < 4 times/week and departing from footbath routine sometimes or often were associated with increased odds for both infectious lesions and lameness. Footbath

use has been demonstrated to be an effective management practice in the control and reduction of DD through intervention trials (Relun et al., 2012; Solano et al., 2017b). It has also been reported that weekly footbath use has increased efficacy compared to less frequent use (Speijers et al., 2010). However, there is immense variation when it comes to footbath management as the numerous factors to consider include footbath dimensions, liquid depth, product, concentration, renewal rate of product, and footbath frequency (Cook et al., 2012). The most superior footbath protocol that encompasses all these factors, therefore, remains undetermined (Jacobs et al., 2019). The current study determined a frequency of < 4 times/week to be a risk factor when compared to a frequency of > 4 times/week. All herds enrolled in this study had a footbath and 98% of herds had a weekly routine of footbath use, which perhaps allowed for enough power to detect the difference reported between these two groups, despite both having good footbath frequency as deemed by previous studies (Speijers et al., 2010; Relun et al., 2012). This result should be interpreted with care as some producers may follow the suggestion of determining their footbath frequency to be based on herd prevalence of DD (DairyCo, 2009; Speijers et al., 2010), however this practice requires regular and consistent monitoring of the herd. While footbath use is agreed to be beneficial for control of infectious lesions, there have been few and mixed reports on the association between footbath management and lameness. Some studies have reported no association between footbath use and lameness (Holzhauer et al., 2006; Solano et al., 2015), and there is one report of increased footbath frequency being a risk factor for lameness (Chapinal et al., 2013a). Upon comparison of numerous footbath protocols, product and concentration were the main focus, and thus future research is required on other aspects of a footbath protocol, including frequency (Jacobs et al., 2019). This future research would be beneficial for lameness as well, due to the mixed reports of footbath use and frequency.

After score adjustment, the RAQ remains to lack the accuracy in identification of overall farm-specific risk for lameness. Although the RAQ contains numerous questions identifying risk factors based on previous studies, it may be possible that some risk factors are not always definite, due to the variation that exists in management practices and facility design between farms, regions, and dairy industries. However, the management and facility questions that were not associated with lameness or lesion prevalence should still be considered given previous reports of their associated risk and biological plausibility. In this study, some questions that had no association with the outcomes may have also been due to the distribution of herds among the categorical answers not allowing for an appropriate analysis of those particular risk factors. This can also be an explanation for why some risk factors were determined to be protective. For example, damp bedding in the lactating cow facility, as represented by only 6 herds, being protective compared to 59 herds with dry bedding. This example may also be explained by the potential bias that results from voluntary participation of herds and the increased likelihood of better management practices. There is also the possibility of management questions that were answered by producers having a level of inaccuracy, regarding selection of the answer that best represents them, and may have biased some resulting odds ratios. Lastly, there may be risk factors that were not included in the RAQ, that if included, may have helped improve overall accuracy, such as grooved flooring (Palmer and O'Connell, 2015), and footbath product and concentration level (Cook, 2017).

The cross-sectional study design is a limitation, because it does not allow causal inferences of the identified risk factors in the RAQ. This can also result in biased odds ratios if a management practice or facility change was implemented close to the time of data collection, and its impact was not fully reflected in herd prevalence yet as it can take time to see results.

This is especially important to consider with claw horn lesion development, from the time of damage to the corium and disruption in claw horn to observing clinical signs (Greenough, 2007). In the case of DD development, specifically the active M2 stage, it can take over 130 days in the absence of footbath management (Krull et al., 2016). Although sample size was large on the cow-level, another limitation was the low number of herds enrolled in the current study. Increased herd observations would have improved the statistical power of comparisons among multiple answer categories and reduced the need to combine categories.

The strong association between herd-lameness prevalence and prevalence of cows with multiple non-infectious lesions recorded within a year supports the idea that recurrence of these lesions predisposes a cow to future lameness events and plays a large role in contribution to overall lameness in the herd. Therefore, keeping track of how many times a cow is diagnosed with a non-infectious lesion can be important as a cow-level predictor for future lameness, similar to previous lameness events being a large contributor to future lameness (Randall et al., 2018). Although the current study was not designed for the thorough investigation of the association between recurrent non-infectious lesions and overall herd prevalence and should be studied further, the importance of cow-level risk factors is clear. A systematic review of risk factors for dairy cattle lameness included 5 factors, of which 4 were on the cow-level (Oehm et al., 2019). These risk factors can be useful to producers in the monitoring of cows that are most vulnerable to lameness. In the current study, the odds of lameness increased with parity, an association that has been previously reported (Solano et al., 2015; Jewell et al., 2019).

3.6 Conclusions

Optimizing the RAQ through efforts to increase its accuracy in identification of overall farm-specific risk for lameness was not successful and requires further research in its question composition and scoring methodology. However, the moderate strength between the non-infectious RAQ score and non-infectious lesion prevalence can be indicative that intervention of the related risk factors would likely result in a reduction of these lesions. Overall, questions in the RAQ that were identified as management and facility related risk factors for lameness and lesions could play a beneficial role in supporting producers with prioritization of changes to implement that will have the largest impact on mitigation. However, cross-sectional studies do restrict the assessment of lameness and lesion causation due to duration of development and their multifactorial nature, thereby making it difficult to determine which risk factors are of ultimate importance.

Table 3.1. Risk factors in the RAQ associated with the presence of lameness, based on univariate logistic regression ($P < 0.05$), before and after the combining of response categories for 65 herds (n = 3,759).

Risk factor	Original categories			After combined (for applicable risk factors)		
	Categories (no. herds)	Odds ratio	*P*-value	Categories (no. herds)	Odds ratio	*P*-value
Pregnant heifer facility bedding depth (Q4.2)	Pasture or > 10 cm (60)	Ref		Pasture or > 10 cm (60)	Ref	
	2 to 5 cm (1)	0.6	0.483	< 10 cm (5)	1.8	0.070
	< 2 cm (4)	2.2	0.018			
Pregnant heifer facility bedding wetness (Q4.3)	Dry (43)	Ref		Dry (43)	Ref	
	Damp (13)	0.9	0.731	Damp (13)	0.9	0.747
	Moderately wet (10)	1.1	0.770	Moderately to very wet (11)	1.2	0.358
	Very wet (1)	4.6	0.018			
Pregnant heifer facility floor slipperiness (Q4.4)	Not at all (58)	Ref		Not at all (58)	Ref	
	Slightly (4)	0.7	0.241	Slightly (4)	0.7	0.246
	Moderately (2)	2.3	0.055	Moderately to very (3)	3.0	0.002
	Very (1)	5.2	0.007			
Percentage of pregnant heifers' hooves examined before calving (Q5.1)	> 80% (17)	Ref				
	50 to 80% (9)	2.2	0.003			
	< 50% (24)	1.3	0.162			
	0% (15)	0.8	0.445			
When pregnant heifer identified as lame or	Immediately (32)	Ref				
	Within 1 week (26)	1.5	0.023			
	At next trimmer visit (7)	1.5	0.130			

has a lesion, when is she treated? (Q5.4)						
Type of dry cow facility (Q6.1)	Pasture or loose housing (55)		Ref			
	Tie stalls or free stalls (10)	1.6	0.038			
Dry cow facility bedding depth (Q6.2)	Pasture or > 10 cm (55)		Ref	Pasture or > 10 cm (55)		Ref
	6 to 10 cm (1)	1.2	0.808	2 to 10 cm (3)	1.0	0.893
	2 to 5 cm (2)	0.8	0.736			
	< 2 cm (7)	2.0	0.008	< 2 cm (7)	2.0	0.008
Floor slipperiness in dry cow facility (Q6.6)	Not at all (55)		Ref	Not at all (55)		Ref
	Slightly (6)	0.9	0.820	Slightly (6)	0.9	0.084
	Moderately (2)	2.4	0.050	Moderately to very (4)	2.8	0.001
	Very (2)	3.4	0.007			
Lactating cow facility bedding wetness (Q8.3)	Dry (59)		Ref			
	Damp (6)	0.5	0.025			
Score for amount of manure on hind leg of 10 randomly selected lactating cows (Q8.11)	Total 5 or less (3)		Ref	Total 10 or less (19)		Ref
	Total 6 to 10 (16)	0.4	0.014			
	Total 11 to 20 (43)	0.6	0.163	Total 11 to 20 (43)	1.3	0.140
	Total 21 to 30 (3)	0.4	0.050	Total 21 to 30 (3)	0.8	0.594
When are lactating cows examined for	When limping or at exam (62)		Ref			

injuries or hoof lesions (Q9.1)	Only when limping (3)	2.7	0.011			
How often each lactating cow walks through a footbath (Q9.4e)	> 4 times/week (34)		Ref	> 4 times/week (34)		Ref
	2 to 4 times/week (30)	1.4	0.039	< 4 times/week (31)	1.4	0.042
	Once/week to once/month (1)	1.1	0.900			
How often footbath schedule is departed from (Q9.4f)	Never (45)		Ref	Never (45)		Ref
	Seldom (13)	1.0	0.899	Seldom (13)	1.0	0.228
	Sometimes (6)	1.6	0.080	Sometimes to often (7)	1.9	0.015
	Often (1)	4.9	0.013			
Average daily duration of required standing time where lactating cows cannot lie down (Q9.5)	30 minutes to 1 hour (25)		Ref			
	1 to 2 hours (37)	1.7	0.002			
	2 to 3 hours (3)	1.0	0.960			

Table 3.2. Risk factors in the RAQ associated with the presence of an infectious lesion, based on univariate logistic regression ($P < 0.05$), before and after the combining of response categories for 63 herds.

Risk factor	Original categories			After combine (for applicable risk factors)		
	Categories (no. herds)	Odds ratio	*P*-value	Categories (no. herds)	Odds ratio	*P*-value
Pregnant heifer facility bedding wetness (Q4.3)	Dry (40)	Ref		Dry (40)	Ref	
	Damp (13)	2.7	0.012	Damp (13)	2.7	0.015
	Moderately wet (9)	0.7	0.444	Moderately to very wet (10)	0.8	0.655
	Very wet (1)	3.5	0.286			
Score for amount of manure on hind leg of 10 randomly selected pregnant heifers (Q4.5)	Total 5 or less (28)	Ref				
	Total 6 to 10 (12)	1.3	0.509			
	Total 11 to 20 (16)	1.8	0.144			
	Total 21 to 30 (7)	3.9	0.013			
Percentage of pregnant heifers' hooves examined before calving (Q5.1)	> 80% (17)	Ref				
	50 to 80% (8)	3.4	0.018			
	< 50% (24)	1.3	0.489			
	0% (14)	1.3	0.584			
How often each lactating cow walks through a footbath (Q9.4e)	> 4 times/week (33)	Ref		> 4 times/week (33)	Ref	
	2 to 4 times/week (29)	1.9	0.041	< 4 times/week (30)	1.8	0.048
	Once/week to once/month (1)	1.0	0.995			
	Never (43)	Ref		Never (43)	Ref	

How often footbath schedule is departed from (Q9.4f)	Seldom (13)	0.9	0.870	Seldom to often (13)	0.9	0.867
	Sometimes (6)	3.2	0.029	Sometimes to often (7)	3.1	0.018
	Often (1)	2.9	0.373			
How many cows pass through a footbath before treatment product is renewed (Q9.4g)	< 100 (4)	Ref		< 200 (29)	Ref	
	100 to 200 (25)	4.0	0.039			
	200 to 300 (24)	2.6	0.135	200 to 300 (24)	0.8	0.618
	> 300 (10)	2.1	0.335	> 300 (10)	0.6	0.237

Table 3.3. Risk factors in the RAQ associated with the presence of a non-infectious lesion, based on univariate logistic regression ($P < 0.05$), before and after the combining of response categories for 63 herds.

Risk factor	Original categories			After combine (for applicable risk factors)		
	Categories (no. herds)	Odds ratio	*P*-value	Categories (no. herds)	Odds ratio	*P*-value
Percentage of pregnant heifers' hooves examined before calving (Q5.1)	> 80% (17)	Ref				
	50 to 80% (8)	1.6	0.038			
	< 50% (24)	1.3	0.106			
	0% (14)	1.3	0.262			
Floor slipperiness in dry cow facility (Q6.6)	Not at all (54)	Ref		Not at all (54)	Ref	
	Slightly (5)	1.2	0.490	Slightly (5)	1.2	0.500
	Moderately (2)	1.4	0.412	Moderately to very (4)	1.9	0.026
	Very (2)	2.6	0.015			
Percentage of dry cows' hooves examined just before dry-off or between dry-off and calving (Q7.1)	> 80% (38)	Ref				
	50 to 80% (14)	1.4	0.020			
	< 50% (11)	1.3	0.107			
Stall base under bedding in lactating cow facility (Q8.1c)	Sand or soil (5)	Ref		Sand or soil (5)	0.6	0.091
	Geotextile mattress or mat (32)	1.6	0.091	Geotextile mattress or mat (32)	Ref	
	Hard rubber or waterbed (17)	1.8	0.037	Hard rubber or waterbed (17)	1.1	0.421
	Concrete (9)	1.8	0.054	Concrete (9)	1.1	0.469

Type of floor surface in animal alleys (Q8.4)	Rubber (2)		Ref	
	Concrete (61)	0.5	0.027	
Type of floor surface on animal-side of feeders (Q8.5)	Rubber (6)		Ref	
	Concrete (57)	0.5	<0.001	

Table 3.4. Final mixed-effects logistic regression model for presence of lameness and associated risk factors from the RAQ for 65 dairy herds in Alberta, Canada (n = 3,641).

Variable (no. herds)[1]	Coefficient	Odds Ratio	90% CI	*P*-value
Parity				
1	Ref			
2	0.43	1.54	1.25 – 1.90	0.001
3	1.40	4.07	3.29 – 5.05	< 0.001
≥ 4	1.96	7.12	5.78 – 8.78	< 0.001
DIM	0.001	1.00	1.00 – 1.00	0.006
Type of floor surface on animal-side of feeders in dry cow facility (Q6.5)				
Stone-free ground (8)	Ref			
Concrete (57)	0.51	1.67	1.10 – 2.52	0.042
Stocking density for lactating cows (Q8.1f)				
< 1 cows/stall (30)	Ref			
1 – 1.1 cows/stall (19)	0.38	1.46	1.06 – 2.01	0.050
1.1 – 1.2 cows/stall (12)	-0.28	0.75	0.53 – 1.08	0.200
> 1.2 cows/stall (4)	-0.35	0.71	0.42 – 1.19	0.273
Leg cleanliness score for 10 lactating cows (Q8.11)				
Total 10 or less (19)	Ref			
Total 11 – 20 (43)	0.48	1.61	1.21 – 2.14	0.006
Total 21 – 30 (3)	-0.69	0.50	0.25 – 0.99	0.097
Footbath liquid depth (Q9.4b)				
> 10 cm (36)	Ref			
< 10 cm (29)	0.33	1.39	1.07 – 1.81	0.041
How often producer departs from footbath schedule (Q9.4f)				
Never (45)	Ref			
Seldom (13)	-0.37	0.69	0.82 – 2.58	0.073
Sometimes to often (7)	0.62	1.86	1.72 – 7.45	0.011

Average daily required standing time for lactating cows (Q9.5)				
30 min – 1 hour (25)	Ref			
1 – 2 hours (37)	0.65	1.91	1.45 – 2.53	< 0.001
2 – 3 hours (3)	0.35	1.42	0.78 – 2.60	0.337

[1] Number of herds for RAQ variable categories

Table 3.5. Final mixed-effects logistic regression model for presence of an infectious lesion and associated risk factors from the RAQ for 63 dairy herds in Alberta, Canada (n = 13,530).

Variable (no. herds)[1]	Coefficient	Odds Ratio	90% CI	*P*-value
Herd avg DIM	0.03	1.03	1.02 – 1.04	<0.001
Herd size				
< 110	Ref			
110 – 164	0.95	2.59	1.47 – 4.55	0.005
≥ 165	1.28	3.60	1.83 – 7.11	0.002
When to examine dry cows' hooves (Q7.2)				
Limping or scheduled exam (45)	Ref			
Only when limping (17)	-0.21	0.81	0.48 – 1.37	0.507
Never examined (1)	-1.93	0.14	0.02 – 0.96	0.093
Stocking density for lactating cows (Q8.1f)				
< 1 cows/stall (30)	Ref			
1 – 1.1 cows/stall (18)	-0.27	0.77	0.46 – 1.28	0.391
1.1 – 1.2 cows/stall (11)	0.06	1.06	0.57 – 1.95	0.881
> 1.2 cows/stall (4)	-1.42	0.24	0.10 – 0.59	0.009
How often producer departs from footbath schedule (Q9.4f)				
Never (43)	Ref			
Seldom (13)	0.38	1.46	0.82 – 2.58	0.279
Sometimes to often (7)	1.28	3.58	1.72 – 7.45	0.004
Average daily required standing time for lactating cows (Q9.5)				
30 min – 1 hour (25)	Ref			
1 – 2 hours (35)	-0.55	0.57	0.35 – 0.94	0.063
2 – 3 hours (3)	-0.58	0.56	0.30 – 1.05	0.129

[1] Number of herds for RAQ variable categories

Table 3.6. Final mixed-effects logistic regression model for presence of a non-infectious lesion and associated risk factors from the RAQ for 63 dairy herds in Alberta, Canada (n = 13,530).

Variable (no. herds)[1]	Coefficient	Odds Ratio	90% CI	*P*-value
Milking frequency				
2 times/day	Ref			
3 times/day	-0.43	0.65	0.52 – 0.82	0.002
Trimming routine				
Partial	Ref			
Whole	-0.46	0.63	0.51 – 0.78	<0.001
Floor slipperiness in dry cow facility (Q6.6)				
Not at all (54)	Ref			
Slightly (5)	0.02	1.02	0.74 – 1.40	0.913
Moderately to very (4)	0.47	1.60	1.12 – 2.27	0.029
Provided feeder space per dry cow (Q6.7)				
Pasture or > 60 cm (53)	Ref			
46 – 60 cm (3)	-0.80	0.45	0.27 – 0.74	0.008
30 – 45 cm (3)	-0.06	0.94	0.67 – 1.34	0.784
< 30 cm (4)	0.07	1.07	0.77 – 1.49	0.743
Stocking density for lactating cows (Q8.1f)				
< 1 cows/stall (30)	Ref			
1 – 1.1 cows/stall (18)	-0.10	0.91	0.75 – 1.11	0.430
1.1 – 1.2 cows/stall (11)	0.01	1.01	0.81 – 1.27	0.916
> 1.2 cows/stall (4)	0.51	1.66	1.22 – 2.25	0.006
Type of floor surface on animal-side of feeders in lactating cow facility (Q8.5)				
Rubber (6)	Ref			
Concrete (57)	-0.81	0.44	0.33 – 0.59	<0.001

Floor slipperiness in lactating cow facility (Q8.8)				
Not at all (22)	Ref			
Slightly (17)	0.19	1.21	0.98 – 1.49	0.143
Moderately (15)	0.26	1.30	1.04 – 1.62	0.054
Very (9)	0.27	1.31	0.99 – 1.74	0.113

[1] Number of herds for RAQ variable categories

Table 3.7. Questions and categories in the RAQ with modified risk scores based on univariate and multivariate model results that increased correlation values for total RAQ score, infectious RAQ score, non-infectious RAQ score, with lameness, infectious, and non-infectious lesion herd-prevalence, respectively.

Question from RAQ	Original risk score	Modified risk score
Q2.1 In past year, have external cattle been brought onto your farm?		
No	0	0
Yes, from 1 source	1	1
Yes, from multiple sources	3	2
Q2.3 Do you require farm visitors to wear disinfected, disposable, or supplied coveralls?		
Yes	0	0
No	3	1
Q2.4 Do you require farm visitors to wear disinfected, disposable, or supplied footwear?		
Yes	0	0
No	3	1
Q4.1 What type of facility are pregnant heifers housed in?		
Pasture, corral or loose housing	0	0
Tie stalls or free stalls	2	1
[1]Q4.3 How wet is bedding and/or ground in pregnant heifer facility?		
Dry	0	0
Damp	1	3
Moderately wet	2	4
Very wet	3	5
[1]Q4.4 How slippery is the flooring or ground in pregnant heifer facility?		
Not at all	0	0
Slightly	1	1
Moderately	2	3
Very	3	4

[1]Q4.5 Score amount of dried manure on outside hind leg of 10 pregnant heifers.		
Total 5 or less	0	0
Total 6 to 10	1	1
Total 11 to 20	2	2
Total 21 to 30	3	4
Q4.6 Are pregnant heifers moved to free stalls immediately after calving?		
No	0	0
Yes	3	1
[1]Q5.1 What percentage of pregnant heifers have their hooves examined before calving?		
More than 80%	0	0
50 to 80%	1	2
Less than 50%	2	3
0%	3	4
[1]Q5.4 When pregnant heifer is identified to be lame or have lesion, when are they treated?		
Immediately	0	0
Within 1 week	1	2
Next trimmer visit	2	3
Not treated	3	4
Q5.5 Are dry cows and pregnant heifers housed together?		
No	0	0
Yes	3	1
Q5.6 Are pregnant heifers fed higher dietary concentrates at least 2 weeks before calving?		
Yes	0	0
No	3	1
Q7.4 Do dry cows walk through a footbath at regular intervals?		
Yes	0	0
No	3	1

Q7.5 Are pregnant heifers fed higher dietary concentrates at least 2 weeks before calving?		
Yes	0	0
No	3	1
[1]Q8.1c In the lactating cow facility, what is the stall base?		
Sand or soil	0	0
Geotextile mattress or resilient mat	1	2
Hard rubber or waterbed	2	3
Concrete	3	4
Q8.1d If free stalls, how do stall widths compare with the standards?		
Equal to or greater than standard	0	0
Less than standard	3	1
[1]Q8.1f What is the stocking density for lactating cows?		
Less than 1 cow/stall	0	0
1 to 1.1 cow/stall	1	2
1.1 to 1.2 cow/stall	2	3
More than 1.2 cow/stall	3	4
Q8.6 What type of floor surface is in the pre-milking holding pen?		
Rubber	0	0
Concrete	2	1
No holding pen	N	N
Q8.7 What type of floor surface is in the area where cows are milked?		
Rubber	0	0
Concrete or metal	2	1
Q8.9 Are lactating cows required to make sharp turns when milking or feeding?		
No	0	0
Yes	2	1

[1]Q9.1 When are lactating cows examined for injuries or hoof lesions?		
When limping or at scheduled exam	0	0
Only when animal is limping	1	3
Only at scheduled exam	2	4
Never examined	3	5
Q9.4d Do you rinse cows' feet before they enter a footbath?		
Yes	0	0
No	2	1
[1]Q9.4e How often does each cow walk through a footbath?		
More than 4 times/week	0	0
2 to 4 times/week	1	2
From once/week to once/month	2	3
Less than once per month	3	4
[1]Q9.4f How often do you depart from this footbath schedule?		
Never	0	0
Seldom	1	1
Sometimes	2	3
Often	3	5
[1]Q9.4g How many cows pass through the footbath before renewing the product?		
Fewer than 100	0	0
100 to 200	1	4
201 to 300	2	5
More than 300	3	6
[1]Q9.5 On average, during the day, how long are cows required to stand?		
30 minutes to 1 hour	0	0
1 to 2 hours	1	2
2 to 3 hours	2	3
More than 3 hours	3	4

Q9.6 Do cows ever experience heat stress?		
No	0	0
Yes	2	1
Q9.7 Are first-calf heifers mixed with older cows when they begin their lactation?		
No, grouped separately	0	0
Yes	2	1

[1]Questions changed based on positive associations with outcomes.

Chapter 4: SUMMARIZING DISCUSSION AND FUTURE PERSPECTIVES

4.1 Summary of results and discussion

This thesis research aimed to evaluate the RAQ by determining how well it identified overall on-farm risk of lesions and lameness, and if improvement or optimization of the RAQ can be done through the quantification of the comprised risk factors followed by necessary adjustments of individual risk factor scores.

Research presented in Chapter 2 and 3 consisted of data collection from 65 participant herds that were visited once between March and October of 2018. Chapter 2 had additional data collected from 10 herds that were visited twice in November 2013 and June 2014. The main objective of Chapter 2 was to determine the RAQ's ability to identify the overall farm-specific risk of lameness and lesions, as measured by the association of total RAQ scores with herd lameness and lesion prevalence. To support the RAQ questions identifying risk for lesions as well as risk for lameness, an additional objective was to determine the cow-level association between presence of a lesion and lameness.

In summary from Chapter 2, the prevalence of lameness was 20%, which is consistent with the prevalence in Alberta last reported (Solano et al., 2015), indicating no change. Lesions were highly associated with lameness, whereby 93% of lame cows also had a lesion. However, only 21% of cows with a lesion were lame. Non-infectious lesions resulted in a 2 times higher likelihood of lameness than infectious lesions, suggesting that not all infectious lesions might be painful enough in the causing of lameness. A previous study reported an association between active DD lesions and lameness, however a cow with an active DD lesion may not necessarily become lame (Krull et al., 2016). Given this knowledge, a lame cow will require intervention

because they will almost certainly have a foot lesion needing treatment, however foot lesion prevalence in the herd will be underestimated if only using lameness as an identifier. The associations between total RAQ scores and prevalence of lameness and lesions were weak, indicating the RAQ was not as accurate as expected and required a further in-depth analysis towards its optimization to better identify overall on-farm risk for lameness.

The main objectives of Chapter 3 were to determine the risk factors in the RAQ that are most associated with lameness and lesions, and whether adjustments to the risk scores of associated risk factors would increase the association between total RAQ scores and prevalence. With recent literature suggesting previous lameness events as a good predictor for future lameness, an additional objective was to investigate the association between prevalence of cows with multiple non-infectious lesions and herd lameness prevalence.

In summary from Chapter 3, a total of 24 risk factors out of 70 presented in the RAQ were positively associated with lameness and/or lesions after univariate and multivariate analyses. However, only 12 of these identified risk factors qualified for changes in risk scores, based on their resulting odds ratios. After adjustments were applied and total RAQ scores were re-calculated, the strength of associations between overall scores and lameness and lesion prevalence improved, however, minimally from the results in Chapter 2. While this suggests the requirement for more research in the scoring method of the RAQ, the associated risk factors identified can be important in having the biggest impact on lameness upon their intervention, and thus can be prioritized by producers in the implementation of strategies for lameness control and mitigation. Additionally, recurrence of non-infectious lesions as indicated by the prevalence of cows with multiple lesions recorded in a year was strongly associated with herd lameness prevalence, suggesting it may be a good predictor in overall lameness. This could be an indicator

of poor recovery from these lesions when in the absence of early intervention, due to the growth of additional bone on the distal phalanx that increases the likelihood of future lesions (Newsome et al., 2016). It is then more likely that these cows are predisposed to future lameness, as it was recently reported that previous lameness events were a large contributor to future lameness events (Randall et al., 2018). Therefore, repeated occurrences of common non-infectious lesions are also likely to be an important contributor to lameness prevalence in the herd.

4.2 Implication of results

As described in Chapter 1, the causes of lameness are mainly attributable to foot lesions (Murray et al., 1996). This was further supported for lameness in Alberta free stall herds with the results of Chapter 2 with 93% of lame cows having the presence of a lesion. Given this knowledge while also recognizing that not all cows with a lesion are lame, many studies have focused on identifying risk factors for foot lesions. For the control and prevention of lameness in Alberta, the RAQ was developed to consist of all known risk factors for lesions, and thus assumed for lameness, for the identification of farm-specific risk that can then facilitate the producer decision-making process by directed intervention strategies. However, studies have not yet determined the accuracy of the RAQ in its overall identification of risk on farm for lameness, as measured by total RAQ scores, or quantified risk factors to determine which ones are most critical. The results of this thesis have implications on the complexity and multifactorial nature of lameness in dairy cattle, as well as support for producers in determining which management and facility risk factors would have the largest impact on lameness upon their intervention, and the additional importance of cow-level factors.

Development of the RAQ was important firstly for initiating discussion between a producer and their advisory team (veterinarian, hoof trimmer etc.) on the topic of lameness in their herd, and what risk factors are present on-farm as identified by the RAQ. This then leads to the decision on a lameness reduction plan, agreed by both the producer and veterinarian, consisting of 3 recommended changes to implement for lameness reduction in the herd. Because these implemented changes can be costly and labor intensive, it is important that the RAQ is accurate in identifying management and facility risk areas that have a strong association with lameness to recommended changes for increased effectiveness in control and mitigation. The results of this thesis research help us to understand that it is not only important to identify risk factors for lameness, but also implicate the need to quantify them to further understand which intervention strategies would have the largest impact on lameness. More knowledge on the latter could help producers tackle lameness in a systematic way. Assessments have been previously reported to be beneficial in helping producers to become aware of the risk on their farms (Morabito et al., 2017). As a step in the right direction, the RAQ is a useful and practical tool composed of all known risk factors for lameness to support producer awareness of their potential presence. Although not all risk factors were associated with the outcomes in this thesis research, they should still be considered.

Another conclusion drawn from this thesis research is the complex relationship between foot lesions and lameness. In Chapter 2, although almost all lame cows had a lesion, less than 25% of cows with a lesion were lame. This implies a disconnect between the identification of a lesion and showing clinical signs of lameness. Cows are known to be prey animals that may suppress signs of pain, and this anomaly could be further complicated by the variation between cows in reacting to a situation differently, such as pain threshold, which was reported for cows

with active DD lesions (Cutler et al., 2013). Although all questions in the RAQ were based on infectious and non-infectious causes of lameness, some questions identified risk factors that were associated with lameness only, and not the lesion of the question's targeted interest (Figure 4.1). Though there are other causes for lameness, including upper limb injury, poor conformation, musculoskeletal joint problems, it is unlikely that these rarer causes can explain this result. This further complicates the relationship between lameness and foot lesions as it would be expected for lesion prevalence to precede lameness prevalence.

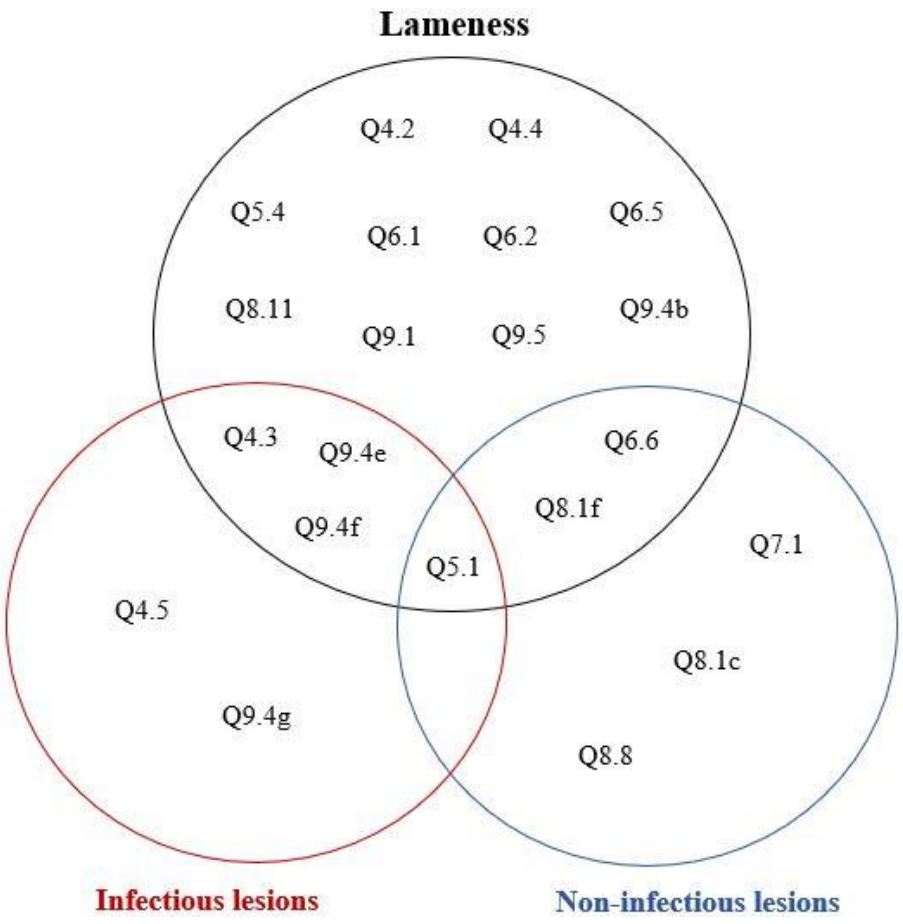


Figure 4.1. Questions in the RAQ associated with lameness, infectious, and non-infectious lesions.

Risk for non-infectious lesions seems less complicated, as the results in Chapter 3 indicate the strongest association between the total non-infectious RAQ score and non-infectious lesion prevalence. Therefore, the RAQ can be viewed as relatively accurate in identifying risk for non-infectious lesions and implemented changes to the associating risk factors should have beneficial results in mitigation. The pathogenesis of infectious lesions remains unclear (Orsel et al., 2018), which could explain the weak association between total infectious RAQ score and infectious lesion prevalence. Given the additional result of non-infectious lesions having higher odds of lameness than infectious lesions, management and facility changes targeted at reducing the risk of non-infectious lesions should also be beneficial in reducing the risk of lameness, more so than changes targeted at reducing the risk of infectious lesions.

Herd-level risk factors for lameness tend to vary among studies, more so than cow-level risk factors. Increasing odds of lameness with increasing parity is consistently reported in previous research (Solano et al., 2015; Jewell et al., 2019) and confirmed by the results of this thesis research. While herd-level risk factors can be acted on by intervention strategies, cow-level risk factors can prove to be very valuable to producers in knowing which cows are most susceptible to lameness and thus, need to be monitored more closely. In addition to parity, keeping track of cows with recurring non-infectious lesions, may be another important cow-level factor in preventing future lameness for those cows. This data is easily accessible for the herds that participated in this research, because WCCHTA hoof trimmers use digital software for efficient record keeping and should be utilized by producers to monitor cows with previous lesion history. This cow-level factor may also be a beneficial addition to the RAQ and potential critical control point for lameness if included as a herd-level measure.

An interesting herd-level result were the increased odds of infectious lesions with increasing herd size. This association was originally hypothesized in Chapter 2 to be due to the idea that larger herds are more likely to be open in the purchase of cattle for their herds, carrying increased risk of infectious lesion introduction to the herd (Oliveira et al., 2017). However, after questions in section 2 of the RAQ (related to external biosecurity) were analyzed in Chapter 3, there was no association determined between the purchase of animals from ≥ 1 source(s) and infectious lesion prevalence. A previous study that determined an association between larger herd sizes and another infectious disease, known as Johne's disease, also had no support for it being due to external biosecurity and instead suggested the idea that some management practices not analyzed could have been dependent on herd size, and thus affecting prevalence (Wolf et al., 2016). This reasoning may apply to the current study, and therefore, the association between infectious lesion prevalence and herd size requires further investigation.

Overall, the RAQ is a practical tool that producers can use for assessing their farm-specific risk of lameness, and the results from this thesis provide information on risk factors that are most associated with lameness and lesions, which can aid a producer's decision on what changes to prioritize implementation. Based on the results in Chapter 3, low lameness prevalence can be achieved with reduced standing time on concrete surfaces by not overstocking and less time in the holding pen, as well as improved environmental hygiene with a consistent footbath schedule to reduce overall infection pressure.

4.3 Thesis limitations

The 65 dairy farm participants were collectively representative of an average dairy farm in Alberta, and thus, were enough for the estimation of lameness and lesion prevalence in

Chapter 2 to have external validity. However, this herd sample size was an important limitation for Chapter 3 when analyzing all possible questions in the RAQ to determine their associations with the outcomes. A larger number of herds enrolled in this thesis research would have been beneficial in detecting important associations and reducing the need to combine answer categories supplied for the questions. However, the herd eligibility criteria for this research were limiting on enrollment, as it resulted in the exclusion of herds with automated milking systems (AMS), loose housing in the lactating cow facility, milk recoding systems other than CanWest DHI, and non-WCCHTA hoof trimmers.

Voluntary participation and required criteria for herd enrollment result in a risk of selection bias. However, most selection criteria were based on traits that represented the majority of dairy farms in Alberta, including a 95% Holstein herd of $\geq$ 40 cows and free stall housing. The requirement of herds to have a WCCHTA hoof trimmer was necessary for consistency in the diagnosis and recording of hoof lesions but resulted in the inability to analyze RAQ questions related to the hoof trimmer because they are consistent with their biosecurity protocols. Another question that was not analyzed was whether the herd routinely walked through a footbath. All herds had footbath management, therefore, the risk of not having a footbath could not be assessed. This could be due to the selection bias present with voluntary participation and/or WCCHTA hoof trimmers communicating the importance of hoof health to producers who value their input. Another explanation could be that footbath management is becoming much more common than it used to.

A limitation of the current thesis research is the cross-sectional study design. It allowed no assessment of causation and had the potential to cause biased associations between risk factors and the outcomes. This can happen if a change to management or facility design occurred

shortly before the date of data collection but may not have had an impact yet on lameness or lesion prevalence. A cross-sectional study can be especially limiting on the outcome of lameness and lesions due to the time it takes in their development from the moment of impact to the observation of clinical signs. The same can be true for recovery time. Visiting and data collection from herds in a longitudinal manner would be beneficial in this field of research.

Another limitation was the assessment of subjective measures in the RAQ or questions answered by producers that could have resulted in misclassification bias. Though most questions aimed to be as objective as possible, subjective questions included floor slipperiness, bedding wetness, and leg cleanliness. However, having one assessor was beneficial in consistency among these measures, and results in Chapter 2 indicated similarity in risk scores between the RAQ conducted for this research and the RAQ conducted by veterinarians. Some questions related to management of pregnant heifers, dry cows, and lactating cows may not have been answered accurately by producers in the instance they were not entirely sure, aware, or honest in their responses. The RAQ is designed to be as inclusive as possible of all herd situations regarding management and facilities with supplied answers, however some answers may lack flexibility of certain situations. For example, the question asking whether sharp turns are present for the lactating cows required a simple ‘yes’ or ‘no’ response. Yet some herds that had a sharp turn present, placed rubber flooring in this area to reduce the risk. This scenario, therefore, could not be captured by RAQ.

4.4 Future perspectives

Lameness has been studied thoroughly in a variety of dairy industries to determine associating risk factors. This is largely done through cross-sectional study designs because they

are less financially and timely demanding. The latter applies to both researchers and producers. However, in the case of lameness being a multifactorial issue and the duration of lesion development, longitudinal studies are becoming of growing importance to determine causation and measure the impact of making changes on herd-lameness and lesion prevalence.

The RAQ is composed of questions targeting risk of management practices and facility design for pregnant heifers, dry cows, and lactating cows. However, the assessment of lameness and lesions was only done for the lactating cows to validate the RAQ. This presents as a limitation and allows for the question of whether inclusion of the pregnant heifers and dry cows in the assessment of lameness and lesions would have provided a stronger association between RAQ scores and prevalence. Therefore, this is something that could explain the weak associations determined in this cross-sectional study design and should be considered for further research. In terms of a more appropriate longitudinal study design, the most appropriate approach would be to follow a prospective cohort study design, starting with pregnant heifers as they progress to entering the lactating herd and understand which management practices and facility areas contribute to high incidence rates of lameness and lesions. As the RAQ was developed as a HACCP approach to lameness prevention, trying to further understand where the critical control points are for a cow from being a pregnant heifer to entering the lactating herd, this study design would play a key role in defining those points.

A different approach to validation of the RAQ should be considered for future research, with the application of cross-validation. This approach would begin with collection of data from one group of study participants and determining the association between RAQ scores and herd prevalence of lameness and lesions (as was done in Chapter 2). With this same data, risk factors in the RAQ with an association are determined, and the risk score weights are changed to address

the increased importance of some risk factors over others (as was done in Chapter 3). However, to appropriately validate the adjusted risk scores in the RAQ, an important next step would be the collection of RAQ (the newly adjusted version) and prevalence data from a new group of study participants. This would allow for a more correct conclusion of whether adjustment of applicable risk factors (potential critical control points) in the RAQ improved the overall identification of on-farm risk for lameness and lesions.

For further quantification of identified risk factors, a study that measures the impact of changes implemented to correct for them by assessing lameness prevalence at consecutive visits over time would be very beneficial. Though the turnover rate of dairies could present a challenge, this type of study could help in the assessment of causation and could also provide a cost-benefit analysis of the implemented changes to support producers with more information on associated costs and effectiveness of interventions. The cost-benefit analysis would play a key role in the decision-making process for lameness prevention and control. Ultimately, change depends on the producer's actions of intervention, therefore, what motivates them is important when determining which factors should be included in a lameness reduction program. Three things are likely to play a large role in motivating producers to adopt intervention strategies, 1) ease of the change; 2) impact of the change and 3) cost of the change. In conclusion, longitudinal studies are important in further understanding which risk factors and their subsequent intervention would meet these criteria for producers to act on in lameness mitigation.

With cow-level factors playing a consistently important role in their association with lameness, longitudinal studies are becoming increasingly beneficial for causal inferences. While some factors cannot be controlled (parity, DIM etc.), this study design could also help to further understand the cow-level relationship between foot lesions and lameness by recording

observations of lesions and lameness over time per cow and determining the impact of recurring lesions on future lesions and lameness.

Appendix 1. RAQ QUESTIONS AND HERD RESPONSES

Question from RAQ	Lameness Prevalence (%)		
	< 20	≥ 20	Total
Q2.1 In the past year, have external cattle been brought onto your farm?			
No	23.1	15.4	38.5
Yes, from 1 source	9.2	18.5	27.7
Yes, from multiple sources	16.9	16.9	33.8
Q2.3 Do you require farm visitors to wear disinfected, disposable, or supplied coveralls?			
Yes	13.8	3.1	16.9
No	35.2	47.7	83.1
Q2.4 Do you require farm visitors to wear disinfected, disposable, or supplied footwear?			
Yes	29.2	18.5	47.7
No	20.0	32.3	52.3
Q2.5 Are heifers ever exposed to manure from lactating or dry cows?			
Yes	1.5	0.0	1.5
No	47.7	50.8	98.5
Q2.6 Does your hoof trimmer clean his chute and tools before entering your premises?			
Yes	49.2	46.2	95.4
No or don’t know	0.0	4.6	4.6
Q2.7 Are trimming tools disinfected after trimming each animal?			
Yes	0.0	3.1	3.1
Don’t know	6.2	12.3	18.5
No	43.1	35.4	78.5

Q4.1 What type of facility are pregnant heifers housed in?			
Pasture, corral or loose housing	46.2	46.2	92.3
Free stalls	3.1	4.6	7.7
Q4.2 On average, how deep is bedding in pregnant heifer facility?			
Pasture or more than 10 cm	46.2	46.2	92.3
6 to 10 cm			0.0
2 to 5 cm	1.5	0.0	1.5
Less than 2 cm	1.5	4.6	6.2
Q4.3 How wet is bedding and/or ground in pregnant heifer facility?			
Dry	30.8	32.3	63.1
Damp	7.7	12.3	20.0
Moderately wet	10.8	4.6	15.4
Very wet	0.0	1.5	1.5
Q4.4 How slippery is the flooring or ground in pregnant heifer facility?			
Not at all	43.1	46.2	89.2
Slightly	6.2	0.0	6.2
Moderately	0.0	3.1	3.1
Very	0.0	1.5	1.5
Q4.5 Score amount of dried manure on outside hind leg of 10 pregnant heifers.			
Total 5 or less	20.0	23.1	43.1
Total 6 to 10	10.8	9.2	20.0
Total 11 to 20	13.8	10.8	24.6
Total 21 to 30	4.6	7.7	12.3
Q4.6 Are pregnant heifers moved to free stalls immediately after calving?			
No	32.3	24.6	56.9
Yes	16.9	26.2	43.1

Q5.1 What percentage of pregnant heifers have their hooves examined before calving?			
More than 80%	16.9	9.2	26.2
50 to 80%	1.5	12.3	13.8
Less than 50%	13.8	23.1	36.9
0%	16.9	6.2	23.1
Q5.2 On average, how often are the hooves of a pregnant heifer examined?			
At least once, more than 1 month before calving	9.2	12.3	21.5
Once, within 1 month of calving	21.5	30.8	52.3
Never	18.5	7.7	26.2
Q5.3 How do you decide when to examine pregnant heifers for injuries or hoof lesions?			
When limping or at scheduled exam	20.0	26.2	46.2
Only when animal is limping	27.7	23.1	50.8
Only at scheduled exam	0.0	1.5	1.5
Never examined	1.5	0.0	1.5
Q5.4 When pregnant heifer is identified to be lame or have lesion, when are they treated?			
Immediately	30.8	18.5	49.2
Within 1 week	13.8	26.2	40.0
Next trimmer visit	4.6	6.2	10.8
Not treated			0.0
Q5.5 Are dry cows and pregnant heifers housed together?			
No	26.2	24.6	50.8
Yes	23.1	26.2	49.2
Q5.6 Are pregnant heifers fed higher dietary concentrates at least 2 weeks before calving?			
Yes	43.1	41.5	84.6
No	6.2	9.2	15.4
Q6.1 What type of facility are dry cows housed in?			
Pasture, corral or loose housing	44.6	40.0	84.6
Free stalls	4.6	10.8	15.4

Q6.2 On average, how deep is bedding in dry cow facility?			
Pasture or more than 10 cm	44.6	40.0	84.6
6 to 10 cm	0.0	1.5	1.5
2 to 5 cm	1.5	1.5	3.1
Less than 2 cm	3.1	7.7	10.8
Q6.3 How wet is bedding and/or ground in dry cow facility?			
Dry	30.8	35.4	66.2
Damp	9.2	12.3	21.5
Moderately wet	7.7	3.1	10.8
Very wet	1.5	0.0	1.5
Q6.4 What type of floor surface is in the alleys in the dry cow facility?			
Stone-free ground, sand or bedded pack	40.0	38.5	78.5
Rubber			0.0
Concrete	9.2	12.3	21.5
Q6.5 What type of floor surface is on animal side of dry cow feeders?			
Stone-free ground, sand or bedded pack	7.7	4.6	12.3
Rubber			0.0
Concrete	41.5	46.2	87.7
Q6.6 How slippery is the flooring in dry cow facility?			
Not at all	43.1	41.5	84.6
Slightly	6.2	3.1	9.2
Moderately	0.0	3.1	3.1
Very	0.0	3.1	3.1
Q6.7 How much feeder space is provided per dry cow?			
Pasture or more than 60 cm/head	43.1	41.5	84.6
46 to 60 cm/head	3.1	1.5	4.6
30 to 45 cm/head	1.5	3.1	4.6
Less than 30 cm/head	1.5	4.6	6.2

Q6.8 Score amount of dried manure on outside hind leg of 10 dry cows.			
Total 5 or less	23.1	26.2	49.2
Total 6 to 10	10.8	15.4	26.2
Total 11 to 20	10.8	7.7	18.5
Total 21 to 30	4.6	1.5	6.2
Q7.1 What percentage of dry cows get their hooves examined just before dry-off or calving?			
More than 80%	26.2	32.3	58.5
50 to 80%	13.8	7.7	21.5
Less than 50%	9.2	10.8	20.0
0%			0.0
Q7.2 How do you decide when to examine dry cows for injuries or hoof lesions?			
When limping or at scheduled exam	35.4	35.4	70.8
Only when animal is limping	12.3	15.4	27.7
Only at scheduled exam			0.0
Never examined	1.5	0.0	1.5
Q7.3 When dry cow is identified to be lame or have lesion, when are they treated?			
Immediately	27.7	18.5	46.2
Within 1 week	16.9	27.7	44.6
Next trimmer visit	4.6	4.6	9.2
Not treated			0.0
Q7.4 Do dry cows walk through a footbath at regular intervals?			
Yes	1.5	10.8	12.3
No	47.7	40.0	87.7
Q7.5 Are pregnant heifers fed higher dietary concentrates at least 2 weeks before calving?			
Yes	43.1	41.5	84.6
No	6.2	9.2	15.4

Q8.1 What type of facility are lactating cows housed in?			
Pasture or loose housing			0.0
Tie stalls or free stalls	49.2	50.8	100.0
Q8.1c In the lactating cow facility, what is the stall base?			
Sand or soil	3.1	4.6	7.7
Geotextile mattress or resilient mat	18	15	50.8
Hard rubber or waterbed	15.4	12.3	27.7
Concrete	3.1	10.8	13.8
Q8.1d In the lactating cow facility, how do stall widths compare with the standards?			
Equal to or greater than standard	18.5	16.9	35.4
Less than standard	30.8	33.8	64.6
Q8.1e In the lactating cow facility, how do stall lengths compare with the standards?			
Equal to or greater than standard	47.7	46.2	93.8
Less than standard	1.5	4.6	6.2
Q8.1f What is the stocking density for lactating cows?			
Less than 1 cow/stall	20.0	26.2	46.2
1 to 1.1 cow/stall	12.3	16.9	29.2
1.1 to 1.2 cow/stall	12.3	6.2	18.5
More than 1.2 cow/stall	4.6	1.5	6.2
Q8.2 On average, how deep is bedding in the lactating cow facility?			
Pasture or more than 10 cm	4.6	9.2	13.8
6 to 10 cm	1.5	6.2	7.7
2 to 5 cm	13.8	10.8	24.6
Less than 2 cm	29.2	24.6	53.8

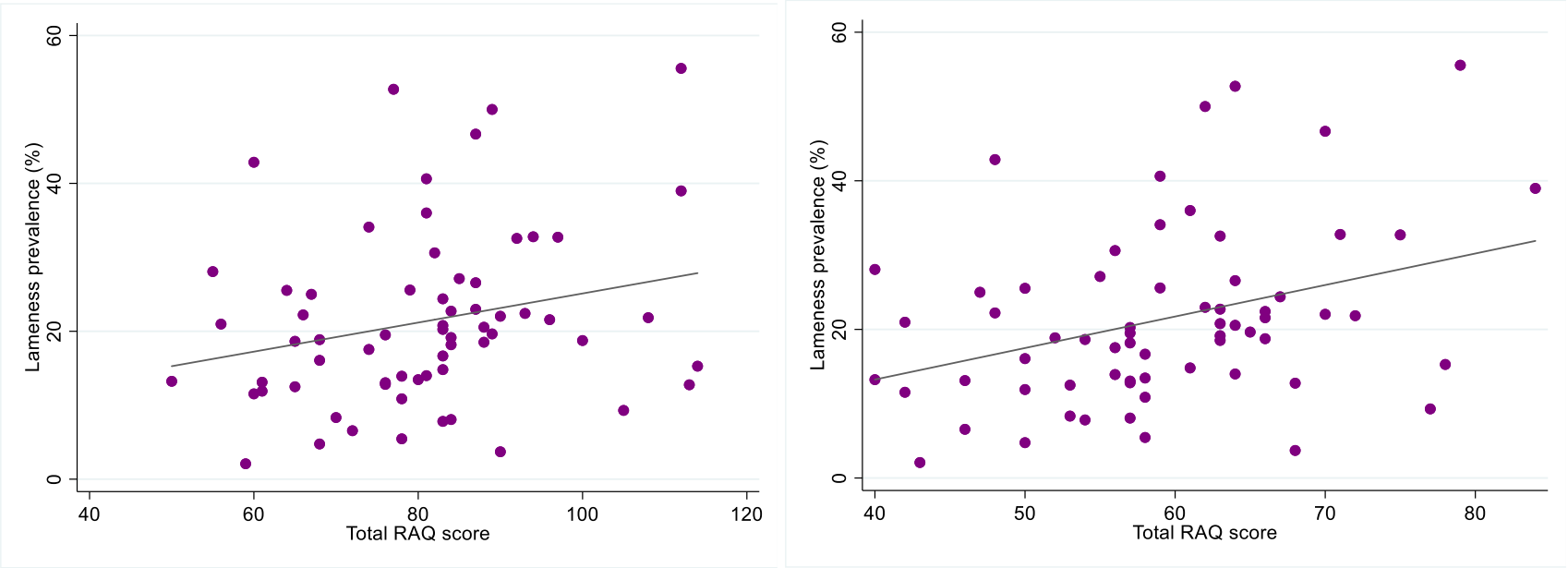
Q8.3 How wet is bedding in lactating cow facility?			
Dry	44.6	46.2	90.8
Damp	4.6	4.6	9.2
Moderately wet			0.0
Very wet			0.0
Q8.4 What type of floor surface is in alleys in lactating cow facility?			
Stone-free ground, sand or bedded pack			0.0
Rubber	3.1	0.0	3.1
Concrete	46.2	50.8	96.9
Q8.5 What type of floor surface is on animal side of lactating cow feeders?			
Stone-free ground, sand or bedded pack			0.0
Rubber	6.2	3.1	9.2
Concrete	43.1	47.7	90.8
Q8.6 What type of floor surface is in the pre-milking holding pen?			
Rubber	12.3	6.2	18.5
Concrete	35.4	41.5	76.9
No holding pen	1.5	3.1	4.6
Q8.7 What type of floor surface is in the area where cows are milked?			
Rubber	13.8	18.5	32.3
Concrete or metal	35.4	32.3	67.7
Q8.8 How slippery is the flooring in lactating cow traffic areas?			
Not at all	21.5	13.8	23
Slightly	10.8	16.9	27.7
Moderately	10.8	12.3	23.1
Very	6.2	7.7	13.8
Q8.9 Are lactating cows required to make sharp turns when milking or feeding?			
No	16.9	20.0	36.9
Yes	32.3	30.8	63.1

Q8.10 How much feeder space is provided per lactating cow?			
More than 60 cm/head	16.9	18.5	35.4
46 to 60 cm/head	15.4	15.4	30.8
30 to 45 cm/head	10.8	10.8	21.5
Less than 30 cm/head	6.2	6.2	12.3
Q8.11 Score amount of dried manure on outside hind leg of 10 lactating cows.			
Total 5 or less	1.5	3.1	4.6
Total 6 to 10	16.9	7.7	24.6
Total 11 to 20	26.2	40.0	66.2
Total 21 to 30	4.6	0.0	4.6
Q9.1 When are lactating cows examined for injuries or hoof lesions?			
When limping or at scheduled exam	49.2	46.2	95.4
Only when animal is limping	0.0	4.6	4.6
Only at scheduled exam			0.0
Never examined			0.0
Q9.2 When lactating cow is identified to be lame or have lesion, when are they treated?			
Immediately	32.3	20.0	52.3
Within 1 week	15.4	27.7	43.1
Next trimmer visit	1.5	3.1	4.6
Not treated	0.0	0.0	0.0
Q9.3 Within a year, how many times does each lactating cow have her hooves examined?			
3 times	6.2	4.6	10.8
Twice	40.0	36.9	76.9
Once	3.1	9.2	12.3
Never			0.0
Q9.4 Do lactating cows routinely walk through a footbath?			
Yes	49.2	50.8	100.0
No			0.0

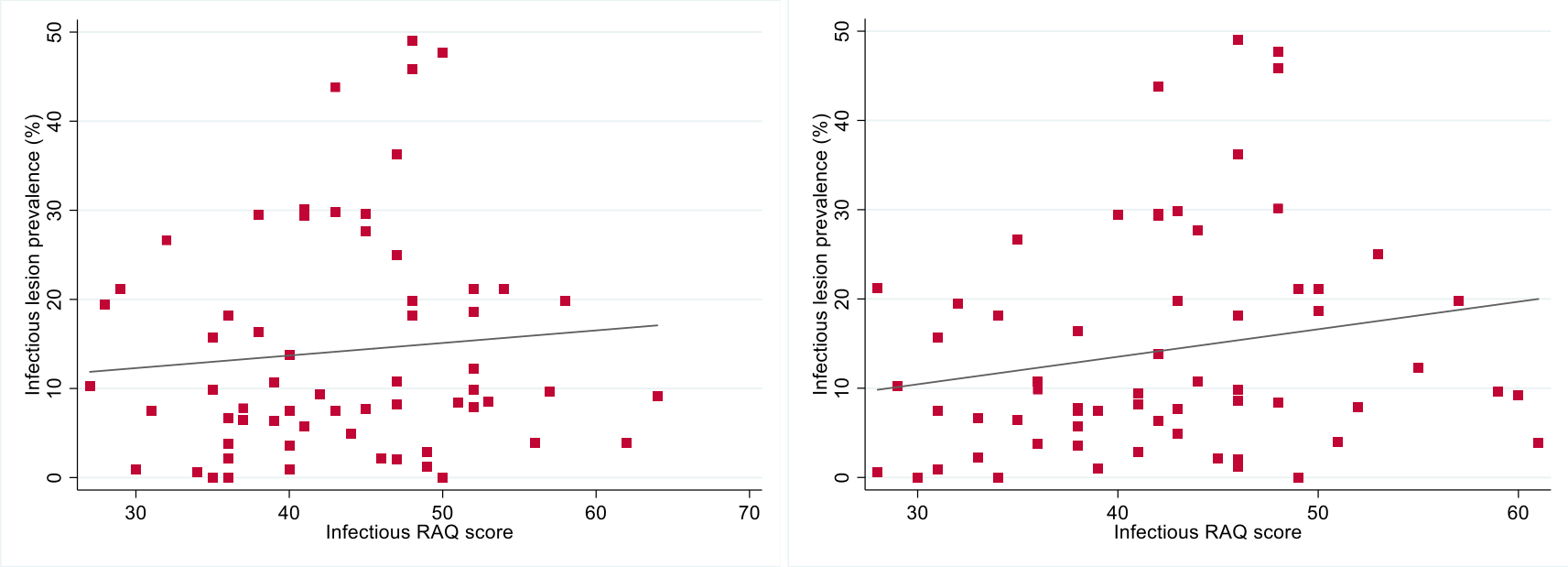
Q9.4a Footbath length:			
More than 3 m	1.5	4.6	6.2
2 to 3 m	29.2	24.6	53.8
Less than 2 m	18.5	21.5	40.0
Q9.4b Footbath liquid depth:			
More than 10 cm	30.8	24.6	55.4
6 to 10 cm	18.5	24.6	43.1
Less than 6 cm	0.0	1.5	1.5
Q9.4c Can cows step around the footbath to avoid submersion?			
No	49.2	47.7	96.9
Yes	0.0	3.1	3.1
Q9.4d Do you rinse cows' feet before they enter a footbath?			
Yes	13.8	18.5	32.3
No	35.4	32.3	67.7
Q9.4e How often does each cow walk through a footbath?			
More than 4 times/week	29.2	23.1	52.3
2 to 4 times/week	18.5	27.7	46.2
From once/week to once/month	1.5	0.0	1.5
Less than once per month			0.0
Q9.4f How often do you depart from this footbath schedule?			
Never	36.9	32.3	69.2
Seldom	9.2	10.8	20.0
Sometimes	3.1	6.2	9.2
Often	0.0	1.5	1.5

Q9.4g How many cows pass through the footbath before renewing the product?			
Fewer than 100	4.6	3.1	7.7
100 to 200	21.5	16.9	38.5
201 to 300	16.9	21.5	38.5
More than 300	6.2	9.2	15.4
Q9.5 On average, during the day, how long are cows required to stand?			
30 minutes to 1 hour	23.1	15.4	38.5
1 to 2 hours	21.5	35.4	56.9
2 to 3 hours	4.6	0.0	4.6
More than 3 hours			0.0
Q9.6 Do cows ever experience heat stress?			
No	24.6	18.5	43.1
Yes	24.6	32.3	56.9
Q9.7 Are first-calf heifers mixed with older cows when they begin their lactation?			
No, grouped separately	12.3	15.4	27.7
Yes	36.9	35.4	72.3

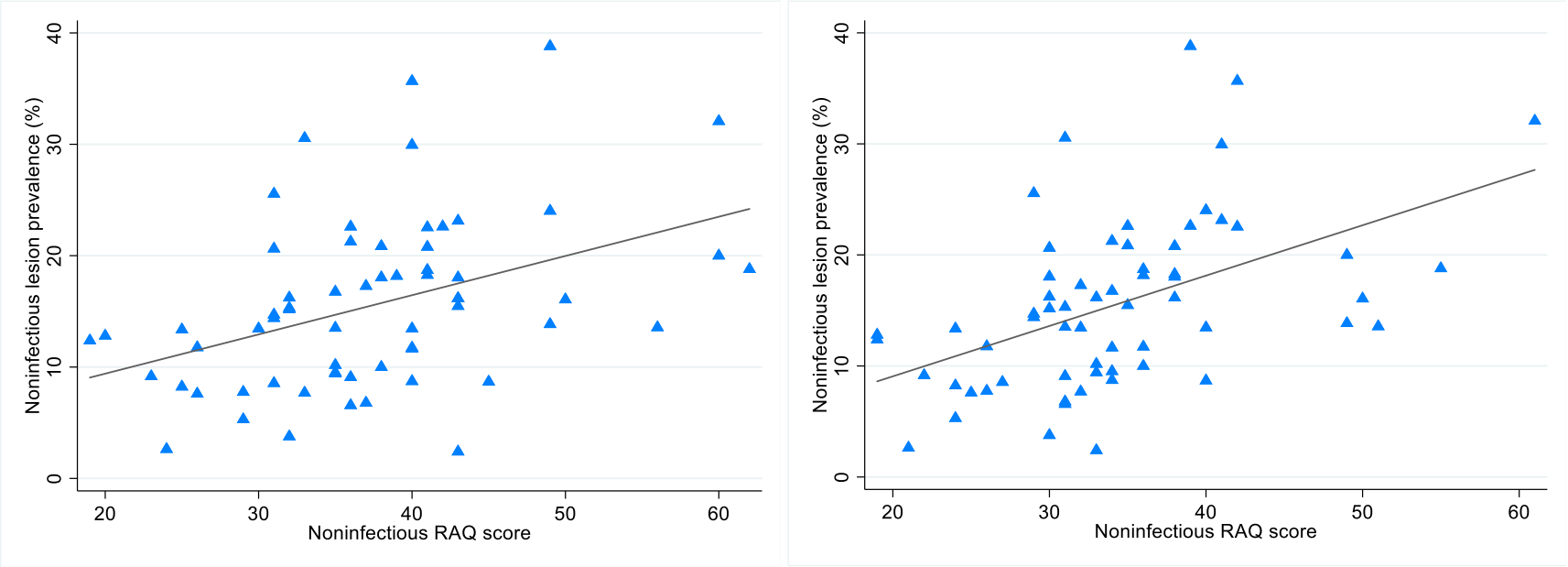
Appendix 2. SCATTERPLOTS OF RAQ SCORES AND PREVALENCE



Lameness prevalence and total RAQ score before and after adjustment of risk scores.



Infectious lesion prevalence and infectious RAQ score before and after adjustment of risk scores.



Noninfectious lesion prevalence and noninfectious RAQ score before and after adjustment of risk scores.

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