EXPLORING THE USE OF TECHNOLOGIES TO ANALYZE COW GAIT AND INVESTIGATING THE EFFECTIVENESS OF OUTDOOR ACCESS ON IMPROVING GAIT AND HOOF HEALTH IN TIE-STALL DAIRY COWS

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ABSTRACT

Hoof and leg disorders are major welfare concerns in dairy cattle. Understanding how current technologies can address these disorders and determining ways in which we can address these issues on farm is crucial for reducing on-farm lameness and improving welfare. The thesis objectives are 1) to map research trends in quantitative bovine gait analysis and to explore the technologies used to measure biomechanical parameters through a systematic scoping review, and 2) to experimentally evaluate how 1h/d of access to an outdoor exercise yard affects gait and hoof health of tie-stall cows.

The scoping review applied PICO framework to conduct a search algorithm through three online databases. Following a two-step screening process, 82 articles were included in the review. Thematic analysis of study research aims yielded four major themes – gait/claw biomechanics, lameness detection, intervention/comparison, and system development/improvement – and three main technology categories – force and pressure platforms, vision-based systems, and accelerometers. Demand for automatic lameness detection influences the path of development for existing quantitative gait analysis technologies; however, more research is needed to achieve more accurate, practical, and user-friendly technologies.

Currently, research into lameness and hoof health is primarily done through experimental studies with animal-based outcomes of hoof and leg health. Such is the case in our study in which we looked at the effect of outdoor access (1h/d, 5d/wk across 5 weeks; Exercise treatment) compared to no access (Non-Exercise treatment) in Holstein lactating tie-stall cows. None of the cows enrolled in the study were clinically lame or had severe claw lesions. Outcomes associated with hoof and leg health were collected across 3 time points (study start, study end, and 8 weeks after) and included gait scoring measures and claw lesion assessment, as well as hoof surface thermography as a new method to detect sub-clinical signs of claw lesions. The overall gait score in Exercise cows improved (2.8 at study start to 1.8 at the study end on a 5-point scoring system), and similar reduction in 3 main gait attributes, although the effect of treatment or time was not significant. There was no difference in the number and severity of claw lesions for both treatment groups over the course of the study. The hoof surface temperature results confirmed the claw lesion inspection: providing 1h of outdoor access for 5 weeks did not lead to a deterioration of claw health. In order to provide different options to farmers, particularly

considering that constant tethering is likely to become unacceptable in the dairy industry in the coming decades, further investigation is needed to look at what frequency or duration of outdoor access would yield positive outcomes for dairy cows.

RÉSUMÉ

Les problèmes des pieds et membres constituent un enjeu de bien-être animal majeur en production laitière. Pour pallier cet enjeu, il importe de développer des stratégies pouvant aider à la réduction de la boiterie à la ferme, et plusieurs technologies aujourd'hui disponibles pourraient y contribuer, pour peu que l'on comprenne de quelle façon nous pouvons les mettre à contribution. C'est dans ce contexte que s'inscrit ce mémoire qui vise à 1) caractériser les tendances actuelles en recherche sur l'analyse de la démarche bovine et dresser le portrait des différentes technologies utilisées pour évaluer des données biomécaniques, à l'aide d'une revue de littérature systématique; 2) évaluer, à l'aide d'une expérience, quel est l'impact d'un accès régulier (1h/j) à une aire d'exercice extérieure sur la démarche et la santé des onglons de vaches laitières logées en stabulation entravée.

La synthèse exploratoire a utilisé le cadre PICO pour conduire une recherche par algorithme au sein de trois bases de données en ligne. Après un tri en deux étapes, 82 articles ont été inclus dans la revue de littérature. Quatre grands thèmes – biomécanique de la démarche/du pied, détection de la boiterie, intervention/comparaison, et développement/amélioration de systèmes – ainsi que trois principales catégories de technologies – plateformes biomécaniques, systèmes basés sur la vision, et accéléromètres – ont été identifiés au terme de l'analyse des objectifs des études. La demande existante pour des systèmes de détection automatique de la boiterie affecte les processus de développement des technologies existantes d'analyse quantitative de la démarche; cependant, plus de recherches seront nécessaires pour obtenir des technologies qui combinent à la fois précision, praticité et convivialité.

Présentement, la recherche sur la boiterie et la santé des onglons s'effectue principalement par le biais d'études sur les animaux au sein desquelles sont collectées diverses mesures de la santé des pieds et membres. Ce fut également le cas de cette étude, par laquelle nous avons évalué l'effet d'un accès régulier à une air d'exercice extérieure (1h/j, 5j/semaine sur 5 semaines; Exercice) comparativement à une absence d'un tel accès (Non-Exercice) chez des vaches Holstein lactantes logées en stabulation entravée. Il n'y avait aucun cas de boiterie clinique ou de lésions sévères aux onglons parmi les vaches recrutées pour l'étude. Des données liées à la santé des pieds et à la locomotion ont été collectées à trois moments différents (début du projet, fin de la phase d'application du traitement, et 8 semaines plus tard); ces données

incluaient une analyse de la démarche, un relevé des lésions des onglons, ainsi que des mesures de la thermographie des pieds, une nouvelle méthode visant à détecter des signes subcliniques des lésions aux onglons. Malgré l'absence d'effet significatif lié aux traitements ou au temps, une amélioration du pointage sommaire de locomotion (2.8 au début de l'étude, 1.8 à la fin; sur une échelle de 5) ainsi que du pointage pour 3 aspects principaux de l'analyse de la locomotion a été observée chez les vaches ayant eu accès à l'exercice. Aucune différence n'a été relevée entre les traitements pour ce qui est du nombre et de la sévérité des lésions aux onglons, et ces résultats ont été confirmés par ceux de la thermographie : fournir un accès à une cour d'exercice extérieure pour 1h/j, 5 j/semaine pendant 5 semaines n'a pas entraîné de conséquences négatives sur la santé des onglons. Plus d'études seront toutefois nécessaires pour déterminer la fréquence et la durée d'accès à l'extérieur qui pourraient amener des résultats positifs pour les vaches laitières; ces données permettront de fournir aux producteurs différentes options pouvant améliorer le bien-être de leurs vaches, tout particulièrement dans un contexte où le confinement permanent à la stalle est de plus en plus mal vu au sein même de l'industrie laitière.

DEDICATION

I dedicate this thesis to all 176 innocent passengers aboard Flight PS752, especially Negar Borghei, a Macdonald campus community member who was unable to finish her academic journey at McGill.

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CONTRIBUTION OF AUTHORS

In this thesis, two multi-authored manuscripts are presented. The authors of both manuscripts 1 and 2, presented as Chapters 2 and 3, respectively, are:

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Amir Nejati was the primary author of manuscripts 1 and 2, and conducted the experiment described in manuscript 2. Amir conducted the search, screening process, and data charting in manuscript 1. Amir performed all video/image observations, processed all thermal images, and compiled and handled all data for manuscript 2. Elsa Vasseur supervised the primary author and reviewed and co-authored both manuscripts. Elsa co-conceptualized manuscript 1 and 2 and provided funding and designed the experiment presented in manuscript 2. Elise Shepley co-supervised the primary author, and co-conceptualized, reviewed, and co-authored both manuscripts. Elise Shepley co-designed the experiment presented in manuscript 2. Anna Bradtmueller co-conceptualized, reviewed, and co-authored manuscript 1. Gabriel Machado Dallago co-conceptualized of statistical analyses and the interpretation of the results relating to the experiment presented in manuscript 2.

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LIST OF ABBREVIATIONS

2D – Two Dimensional

3D – Three Dimensional

AC – Accelerometer

ALDS – Automated Lameness Detection System

AN – Analgesics

BPM – Back Posture Measure

CA – Skin Control Area

CB – Coronary Band

COP – Center of Pressure

DIM – Days in Milk

DOF – Degree of Freedom

DV – Development/Validation

FD – Foot Disorders

FP – Force Platforms

FPP – Force and Pressure Platforms

FT – Flooring Type

GCB – Gait/Claw Biomechanics

GRF – Ground Reaction Force

HFK – High-speed Fluoroscopic Kinematography

HT – Hoof Trimming

IC – Intervention/Comparison

ICAR – International Committee for Animal Recording

IM – Improvement

IP – Image Processing

IR – Infrared detector

IRC – Infrared Camera

LD – Lameness Detection

LMV – Limb Movement Variable

LWR – Leg Weight Ratio

NRS – Numerical Rating System

PICO – Population-Intervention-Context

PMS – Pressure Mapping System

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RFD – Reaction Force Detection

ROI – Region of Interest

ROM – Range of Motion

ScR – Scoping Review

SD – System Development

SLS – Stepmetrix Locomotion Score

STD – Standard Deviation

VA – Video Analysis

VB – Vision-based

VLS – Visual Locomotion Scoring

WDP – Weight Distribution Platforms

CHAPTER 1 – GENERAL INTRODUCTION

In bovine research, the term "gait" generally refers to the locomotion and movement ability of a cow. Deviation from normal gait as a result of hoof and leg disorders is generally defined as lameness. However, in literature, a wide range of terms and definitions (e.g., locomotor disorders, hoof and leg problems, abnormal gait, and impaired locomotion) have been used by researchers in attempts to cover both the causes of lameness, i.e., hoof or leg disorders, and the manifestation of lameness, i.e., abnormal gait (Flower, 2006; Van Nuffel et al., 2015). Lameness is a multifactorial condition involving a mix of housing, on-farm management, and environmental factors (Shearer et al., 2012). Although claw disorders are the most common cause of lameness (Murray et al., 1996), lameness can also be originated from disorders above the foot, such as hock and knee injuries (Nash et al., 2016). Lameness is one of the major issues in dairy cattle due to its severe negative impacts on animal welfare (von Keyserlingk et al., 2009) and health (Booth et al., 2004), and its association with substantial economic losses (Dolecheck & Bewley, 2018). Additionally, lameness is highly prevalent within dairy herds, especially in stall-based housing systems. It is reported that lameness can affect up to 69% of cows housed in free-stall (Solano et al., 2015) and up to 39% of cows housed in tie-stall barns (Gibbons et al., 2014) in Canada.

According to the latest statistics, tie-stall barns accounted for 73% of the total 5,832 recorded dairy farms in Canada, with the remaining percentage consisting mainly of free-stall barns (C.D.I.C. Canadian Dairy Information Centre, 2020). One of the main disadvantages of tie-stall housing systems regarding animal welfare is the lack of sufficient physical activity. A tethered cow is deprived of voluntary movement and is restricted from expressing her natural behavior. Therefore, the dairy industry seeks to provide partial access to additional spaces such as outdoor paddocks, yards, or even indoor facilities to increase movement opportunities for cows. Additionally, the update of the Canadian Code of Practice for the Care and Handling of Dairy Cattle that released in 2019 listed "exercise" and "outdoor access (pasture and alternatives)" as "priority welfare issues" for indoor housing systems (National Farm Animal Care Council (NFACC), 2021). Studies showed that increasing movement opportunity through the addition of outdoor access or pasture in stall-based systems could improve gait and hoof health of cows as well as other animal welfare aspects (Popescu et al., 2013; Shepley, Lensink, &

Vasseur, 2020). However, most of these studies have been conducted in free-stalls, and little research directly evaluated the effect of partial outdoor access on cows confined long-term in tie-stalls.

Part and parcel with looking for ways to address lameness issues in dairy cattle is the use of technologies to more objectively investigate outcome measures related to hoof and leg disorders. Understanding how gait analysis technologies can enhance on-farm management to monitor animal well-being and address cow gait abnormalities is essential for modern dairy farming. Identifying hoof and leg disorders, particularly in the early stages of development, is a critical step in promoting animal health and welfare by early intervention and treatment (Leach et al., 2012). A variety of cow gait analysis technologies have been developed over the last two decades, and researchers in the field of cow gait analysis continue to improve these technologies to find more reliable, accurate and easy on-farm implemented solutions (Alsaaod et al., 2019; Schlageter-Tello et al., 2014). However, subjective gait assessment remains the primary method of cow gait analysis in the research and on-farm settings, despite evidence of the unreliability of these methods (Schlageter-Tello et al., 2014).

1.1. OBJECTIVES

1.1.1. Overall objectives

The main objectives of this thesis were to increase our understanding of the ways in which bovine gait is quantitatively addressed in existing literature and to determine how outdoor access affects the gait and hoof health of tie-stall housed cows.

1.1.2. Specific objectives

Working towards the overall thesis objectives, the objectives of the scoping review included in this thesis were to:

1. Map research trend of quantitative bovine gait analysis
2. Explore the technologies that have been being utilized to measure biomechanical parameters of gait variables in bovine species
3. Spotlight the current gaps in the field of cow gait analysis

Specific objectives of the experimental study on tie-stall housed dairy cows presented in this thesis were to evaluate how 1h/d access to an outdoor exercise yard affected:

1. Overall gait and specific gait-related attributes
2. Hoof health, measured through claw lesion assessment and hoof surface temperature
3. Activity level, based on pedometer-recorded step activity

CHAPTER 2 – TECHNOLOGY APPLICATIONS IN BOVINE GAIT ANALYSIS: A SCOPING REVIEW

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2.1. ABSTRACT

Quantitative bovine gait analysis using technology has evolved significantly over the last two decades. However, subjective methods of gait assessment using visual assessment of cow gait remain the primary on-farm and experimental approach. The objective of this review is to map research trends in quantitative bovine gait analysis and to explore the technologies that have been utilized to measure biomechanical parameters of gait. A scoping literature review was conducted according to PRISMA guidelines. A search algorithm based on PICO framework generated three components – bovine, gait, and technology – to address our objective. Three online databases were searched for original work published from January 2000 to June 2020. A two-step screening process was then conducted, starting with the review of article titles and abstracts based on inclusion criteria. A remaining 125 articles then underwent a full-text assessment, resulting in 82 final articles. Thematic analysis of research aims resulted in four major themes among the studies: gait/claw biomechanics, lameness detection, intervention/comparison, and system development. Lameness detection (55 % of studies) was the most common reason for technology use. Studies in the field of bovine gait analysis used three main technologies: force and pressure platforms (FPP), vision-based systems (VB), and accelerometers. FPP were the first and most popular technologies to evaluate bovine gait and were used in 58.5 % of studies. They include force platforms, pressure mapping systems, and weight distribution platforms. The second most applied technology was VB (34.1 % of studies), which predominately consists of video analysis and image processing systems. Accelerometers, a more novel technological method to measure gait characteristics, were used in 14.6 % of studies.

A strong demand for automatic lameness detection influences the path of development for quantitative gait analysis technologies. Although progress has been made, more research is needed to achieve more accurate, practical, and user-friendly technologies.

2.2. INTRODUCTION

Gait abnormalities are a major welfare concern that cause considerable economic losses in cattle farming (Dolecheck & Bewley, 2018; Whay et al., 2003). Hoof and leg disorders are the most common cause of gait abnormalities – mainly known as "lameness" in literature (Schlageter-Tello et al., 2014; Van Nuffel et al., 2015). Identifying cows with impaired locomotion, especially at early stages of development, is key to minimizing the welfare and economic consequences of gait abnormalities (Leach et al., 2012). The prevalence of lame cows is often underestimated by farmers who only rely on passive observation of cows for abnormal gait (e.g., visual assessment when moving cows for milking), which is not sufficient for identifying the lame cows (Cutler et al., 2017), particularly in the case of mild lameness and early lameness detection. Gait analysis can be used to facilitate and improve lameness detection in cows (Whay, 2002). Besides the role of gait analysis in identifying a lame cow, it can also be utilized in research to investigate cow's welfare and ease of movement under different conditions (e.g., housing systems, Shepley and Vasseur (2021b); flooring type, Telezhenko and Bergsten (2005)).

Generally, gait analysis is conducted through subjective (qualitative) and objective (quantitative) methods. Subjective methods, i.e., visual gait scoring, is the traditional and primary method of gait analysis as it is easy and inexpensive to implement both on-farm and in research studies. However, visual gait scoring is subjective in nature and, as such, variability in the observer's training level and background experience and the wide range of different gait characteristics may contribute to low intra- and inter-observer reliability (Brenninkmeyer et al., 2007; Engel et al., 2003; Schlageter-Tello et al., 2014). In addition, visual gait scoring is a time-consuming procedure, particularly in large herds, which may lead to producers conducting less frequent assessments of gait, resulting in later detection of lameness and, thus, hindering early intervention and treating (Schlageter-Tello et al., 2014). Objective methods using gait analysis technologies have been developed by researchers over the years to address the weaknesses of the traditional methods of cow gait assessment. However, exploring and appraising studies that utilize gait analysis technologies and drawing comparisons between their outcomes is difficult. This is due not only to the variety of ways in which gait analysis technologies are applied in research and the outcome measures investigated, but also due to differences in hardware and settings within similar types of technology that complicate comparisons even when the same category of gait analysis technology is used. Moreover, although several efforts have been made to put forth systematic reviews on cow gait analysis technologies, these looked primarily at studies in which cow lameness is the central focus. There is a lack of systematic reviews that considers all aspects of direct cow gait and movement analysis, independent of cow lameness.

The scoping review has become an increasingly popular approach for synthesizing research evidence and its use in animal sciences is increasing, with journals now putting forward specific guidelines for conducting scoping reviews (e.g., Journal of Dairy Science). It is a descriptive study design and a relatively new approach to chart or map the literature. The objective of this scoping review was to map research trends of quantitative bovine gait analysis, to explore the technologies that have been being utilized to measure biomechanics parameters of gait variables in bovine species, and to spotlight the current gaps in the field of cow gait analysis.

2.3. METHODS

2.3.1. Protocol

The protocol for this review was formatted as per the items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews, i.e., PRISMA-ScR (Page et al., 2021).

2.3.2. Eligibility criteria

English language full text publications of primary research from any geographic location were included without restrictions on study design. Publications dated prior to 2000 were excluded due to substantive changes that occurred since that time in bovine gait practices. We included research conducted on live cow populations (in vivo studies) for either beef or dairy cattle with no age and production cycle limitation. Only studies that measured gait attributes objectively through technologies using biomechanical parameters derived from kinematic and kinetic analysis were included in the review.

2.3.3. Information sources and search strategy

To identify references, the literature search was conducted in three electronic databases (Web of Science Core Collection, CAB Abstracts, and Scopus). A comprehensive search strategy was developed in order to identify relevant literature. Search terms were developed based on PICO framework in which three main components were extracted from the original research question. The target population (first component) is bovine species in which we are looking for the intervention of technology (second component) in the context of gait analysis (third component).

Afterwards, nine domains were included in the search. These domains were bovine, gait analysis, locomotion analysis, movement analysis, lameness detection, biomechanics, vision-based analysis, accelerometer, and measuring plates. The search algorithm applied the following combination of these nine domains: (bovine) AND [(gait analysis) OR (locomotion analysis) OR (movement analysis) OR (lameness detection)] AND [(biomechanics) OR (vision-based analysis) OR (accelerometer) OR (measuring plate)]. Then, in the selected databases, article titles, abstracts and keywords using the nine domains with several possible keywords for each were looked at. Table 2.3.1 shows the details of the search strings conducted in the Web of Science database as an example. The same search strategy was translated into the CAB Abstracts and Scopus databases.

The final search was conducted on June 2, 2020. For this search, no limits were set on language, subject area, study design or date of publication to allow for the minimization of bias in identifying all relevant research for inclusion in the review.

Table 2.3.1. List of the different strings included in the search strategy and the number of retrieved references for each string. Application on the Web of Science database on June 2, 2020.

#	String	Records found
# 1	TS=(cow$ OR bovine OR cattle OR heifer$ OR calf OR calves)	595,051
# 2	TS=((movement NEAR/15 analys*) OR (movement NEAR/15 evaluat*) OR (movement NEAR/15 measur*) OR (movement NEAR/15 assess*))	42,272
# 3	TS=((locomot* NEAR/15 analy*) OR (locomot* NEAR/15 evaluat*) OR (locomot* NEAR/15 measur*) OR (locomot* NEAR/15 assess*))	13,507
# 4	TS=((gait NEAR/15 analy*) OR (gait NEAR/15 evaluat*) OR (gait NEAR/15 measur*) OR (gait NEAR/15 assess*))	9,519
# 5	TS=((lameness NEAR/15 detect*) OR (lameness NEAR/15 evaluat*) OR (lameness NEAR/15 measur*) OR (lameness NEAR/15 identif*))	1,252
# 6	TS=(kinesi* OR kinetic$ OR kinemat* OR biomechanic$)	595,051
# 7	TS=(acceler* OR sensor$)	1,451,335
# 8	TS=((force NEAR/15 (plate$ OR mat$)) OR (sensitive NEAR/15 (plate$ OR mat$)) OR (pressure NEAR/15 (plate$ OR mat$)) OR GRF OR (ground NEAR/15 force))	14,549
# 9	TS=(3$d OR 3$dimension* OR three$dimension* OR 2$d OR 2$dimension* OR two$dimension* OR (video$ NEAR/15 (process* OR analy* OR based)) OR (image$ NEAR/15 (process* OR analy* OR based)) OR (vision NEAR/15 (based OR computer)))	586,120
	#1 AND (#2 OR #3 OR #4 OR #5) AND (#6 OR #7 OR #8 OR #9)	280

A supplementary search was performed using handsearching to pick up any relevant references that were missed by the database searches. Subsequently, the reference lists of each of the documents found to meet the inclusion criteria were also screened to identify any additional documents of interest.

2.3.4. Selection of sources of evidence

All references were imported into the Endnote X9 reference management software (The EndNote Team, 2013) and duplicates were removed. All literature was then uploaded to

Covidence, an online systematic review management program (Oosterlinck et al., 2010). The review was then performed in two steps. The first consisted of a review of titles and abstracts through which papers unrelated to the research questions (n=349) were excluded. Articles related to the topic of bovine gait and movement analysis or lameness detections were all included in the next step of screening process. The second step consisted in a full-text review to make sure that the references all meet the eligibility criteria. Further exclusion of the documents was performed during the data collection process (i.e., a document could be later excluded based on its full-text review). Figure 2.4.1 summarizes the selection process.

2.3.5. Data charting process and data items

A data extraction sheet developed by the authors was used to chart literature under the following headings: author(s), title, year published, journal, research aims, research setting (laboratory or farm-based), used technologies, hardware (device, specifications), types of animal pre-preparation (e.g., marker or sensor attachment), target anatomical regions, test corridor (dimensions, flooring, number of steps), housing system, flooring type, sample size, breed, age, production cycle (dry or lactating), measured variables, main findings, study limitations, and future directions.

All the screening and data extraction steps were performed by a single reviewer. To minimize the likelihood of human error, all the uncertainties during the review process as well as the initial development of the scoping review protocol were discussed with the reviewer team on a weekly basis.

2.3.6. Synthesis of results

A narrative synthesis was used to collate, summarize, and present the findings of the current review. Various tools and approaches such as thematic analysis, textual descriptions, tabulation, and graphs were used to explore similarities, differences, and relationships between different studies. Literature data were analyzed using a thematic analysis approach to map research aims. The included articles were coded accordingly based on the objectives they aimed to address. Major themes, subthemes, and their corresponding codes and definitions were developed by the review team. A thematic analysis approach was similarly employed in the analysis of the gait assessment technologies.

2.4. RESULTS

2.4.1. Selection of sources of evidence

A total of 729 articles were retrieved from three databases and other sources (316 from Scopus, 280 from Web of Science Core Collection, 113 from CAB Abstracts, and 20 from the other sources). The de-duplication process left 474 records to screen. After screening abstracts and titles, we excluded 349 publications that were not related to field of bovine locomotion evaluation. By examining the remaining 125 in detail, a further 43 were excluded. Therefore, a final number of 82 articles were included in the scoping literature review. Figure 2.4.1 shows the PRISMA flow diagram for the study's selection method.

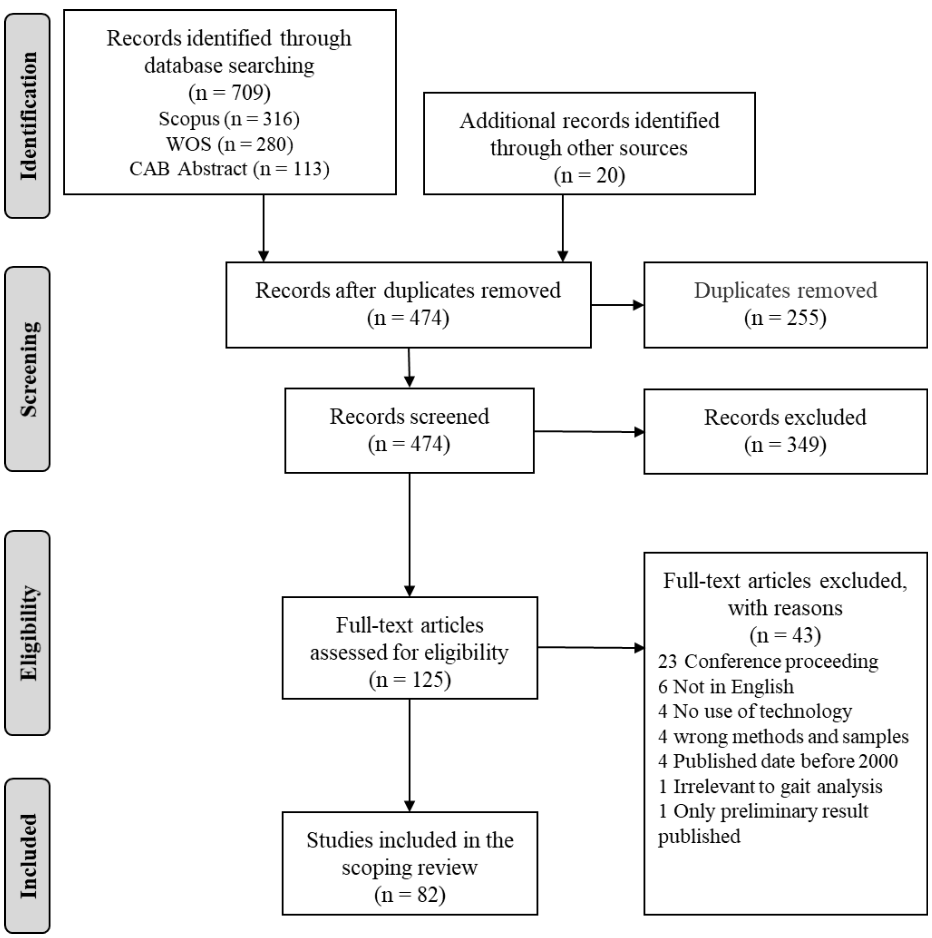

Figure 2.4.1. PRISMA flow diagram for scoping reviews showing literature search and selection of articles.

2.4.2. Characteristics of sources of evidence

2.4.2.1. Origin of datasets

The 82 included articles were published between 2000 and 2020, with the majority of articles (93%) published after 2005 (Figure 2.4.2). Datasets presented in the articles originated from 16 countries, with most originating from the United States (n = 16 articles; 19.5%), followed by Belgium and Canada (n = 12 articles; 14.6% and n = 11 articles; 13.4% respectively).

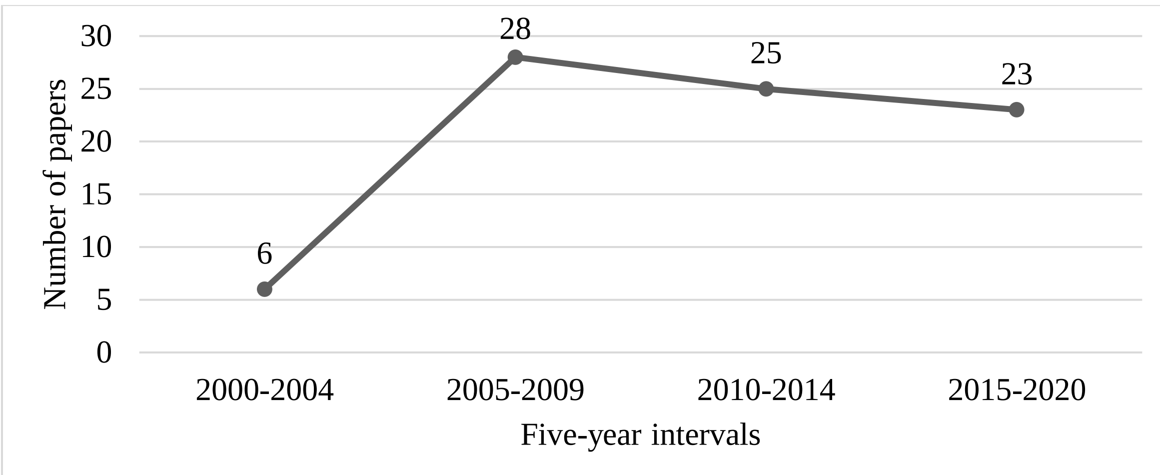

Figure 2.4.2. Number of included articles published over five-year intervals from 2000 to 2020.

2.4.2.2. Publication journals

Articles included in this review were published across 23 scientific journals. Journal of Dairy Science was the journal with the most articles included in this review (n = 33 articles; 40%), followed by Computers and Electronics in Agriculture (n = 10 articles; 12%).

2.4.3. Synthesis of results

2.4.3.1. Research aim

To understand the importance of using technology in bovine gait analysis, it is necessary to (first) examine the objectives of studies that have used these technologies. Therefore, a thematic analysis of research aims was conducted based on the objective(s) that were stated in the studies. Table 2.4.1 shows the thematic classification of research aims/themes, each theme was coded and described. There were four major themes: Gait/Claw biomechanics (GCB), Lameness detection (LD), Intervention/Comparison (IC), and System development (SD). Three of major themes had subheadings. These were 1) Lameness detection: visual locomotion Scoring (LD-VLS), foot disorders (LD-FD), and automatic lameness detection systems (LD-ALDSs); 2) Intervention/Comparison: flooring type (IC-FT), hoof trimming (IC-HT), analgesics (IC-AN), and other (IC- Other); and 3) System development: development and validation (SD-DV), and system improvement (SD-IM).

Lameness detection, i.e., identifying lame cows or an impaired limb using technology, was the most frequent research aim pursued in the gait analysis literature with 45 studies (55%, Table 2.4.1), followed by Intervention/Comparison studies (29 studies, 35.5%) and System development studies (20 studies, 24.5%). Studies that aimed to explore gait/claw biomechanics of a non-lame cow using a technology accounted for the lowest number of studies (9 studies, 11%) in the bovine gait analysis literature. The trend of four major research aims/themes (Figure 2.4.3) illustrates that lameness detection has maintained its dominance over the other research objectives for the last 15 years.

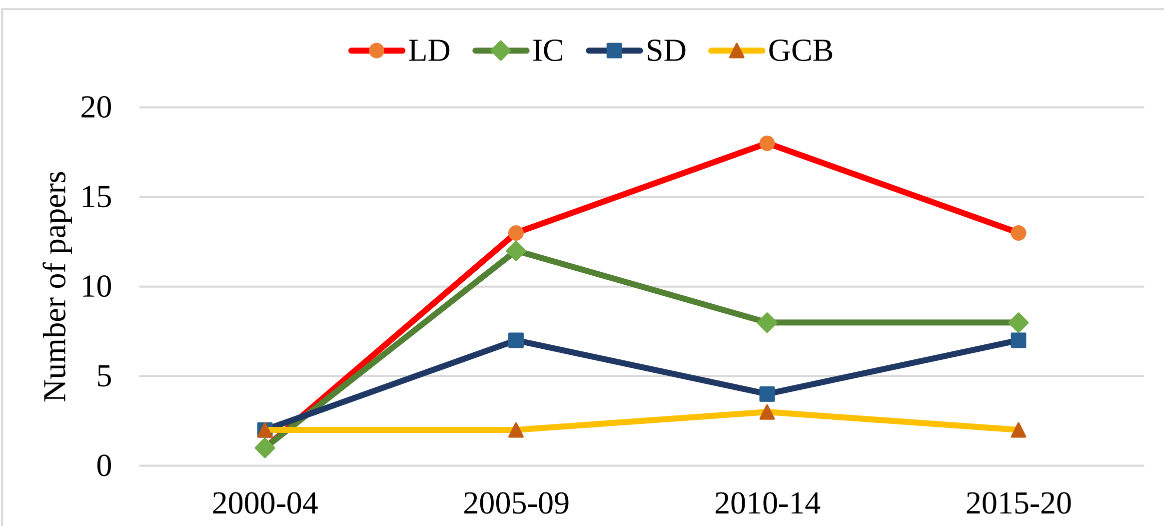

Figure 2.4.3. Research aim plotted over 5-year bins from 2000–2020. Lameness detection (LD), Intervention/Comparison (IC), System development (SD), Gait/claw biomechanics (GCB).

Table 2.4.1. Published trends in bovine biomechanical research, with findings derived from thematic analysis of stated research aims of the 82 included articles. Some papers were categorized under more than one main theme or subtheme (i.e., they aimed more than one objective).

Major theme	Subtheme	Description	N	%
Gait/Claw biomechanics (GCB)		Exploring biomechanics of sound (Non-lame) animals while walking or standing naturally.	9	11
Lameness detection (LD)		Utilizing technology to distinguish between lame and non-lame cows and identifying the impaired limb.	45	55
	ALDS	Investigating lameness detection methods using automated lameness detection systems.	35	42.5
	VLS	Using visual locomotion scoring for identifying a lame cow.	36	44
	FD	Using foot disorders, i.e., foot pathologies, hoof lesion, and hoof pain, for identifying a lame cow.	18	22
Intervention/ Comparison (IC)		Investigating/comparing gait alterations before and after an intervention or between different set-ups.	29	35.5
	FT	Comparing gait across different flooring types.	10	12
	HT	Examining the gait measures before and after Hoof trimming.	8	10
	AN	Investigating the effect of local or systemic analgesics on gait.	7	8.5
	Other	Investigating the effect of other circumstances on gait such as diet, walking speed, hoof treatment block, milking, calving, etc.	5	6
System development (SD)		Research aiming to develop a system.	20	24.5
	DV	Developing and/or validating a new system.	14	17
	IM	Enhancing an existing system by improving the material and methods used or by using various statistical models	6	7.5

Abbreviations: ALDS: automatic lameness detection system; VLS: visual locomotion scoring; FD: foot disorders; FT: flooring type; HT: hoof trimming; AN: analgesics; DV: development - validation; IM: improvement.

2.4.3.2. Gait analysis technologies

Three main technologies employed in bovine gait analysis including force and pressure platforms (FPP), vision-based technologies (VB), and accelerometers. Table 2.4.2 shows an overview of these technologies and their subcategories that will be explained in detail further in this review.

Table 2.4.2. Three main gait analysis technologies and their subcategories.

Main technology	Subcategory	N	%
Force & pressure platforms (FPP)		48	58.5
	Force Platforms (FP)	18	22
	Pressure Mapping Systems (PMS)	19	23
	Weight distribution platforms (WDP)	15	18.5
Vision-based (VB)		28	34
	Video Analysis (VA)	13	16
	Image Processing (IP)	13	16
Accelerometers		12	14.5

2.4.3.2.1. Force and Pressure Platforms (FPP)

Force, pressure, and weight, along with their derivatives, are the main kinetic attributes measured by floor-sensitive plates. These measures are taken either when an animal is walking over the plates (dynamic measurements) or when standing on them (static measurements). The use of these technologies in bovine biomechanical analysis dates back to the early 1970s, with research from 1970-2000 focused primarily on evaluating load distribution between legs and claws. After 2000, these measuring plates became the most widely used technology (48 studies, 58.5%) in bovine biomechanical analysis. In the current review, these technologies are classified into three main groups: force platforms (FP), pressure mapping systems (PMS), and weight distribution platforms (WDP).

2.4.3.2.1.1. Force Platforms (FP)

Force platforms use force transducers, also known as load cells, to measure vertical or three-dimensional ground reaction forces (GRF) applied over the platform’s top surface. There are 18 bovine gait analysis studies that have used different FP types, and these vary in the type and number of force transducers. While not all studies specified the types of FP used, platforms comprised of four transducers fixed to the four corners of the plate are the most common. However, the technology has also been applied in other forms, such as a 3D force plate consisting of 7 force transducers to measure longitudinal, transversal, and vertical GRF. The Emfit (Pastell et al., 2008), which is comprised of a thin sensing element of ferroelectret film, is another type of FP. Additionally, Meyer et al. (2007) used a treadmill-integrated force measuring system equipped with eighteen force transducers (9 on each side) to measure GRF while cows were walking at a controlled speed.

Most studies used more than one force plate placed next to each other to allow for bi-lateral and/or individual hoof measurements of force. However, three studies had used a single force plate, which allowed for the evaluation of only one side of the animal (i.e., the fore and hind limbs of one side) during a measurement. The length of the force platforms varies between the studies that have reported platform dimensions, typically ranging from 0.9 to 2 m. Walker et al. (2010) used a 3-meter-long force platform by placing 5 smaller force plates (each 0.6 m long) in a row to measure multiple consecutive footfalls. Force data recording rate also had considerable variation among the studies that reported it, ranging from 50 Hz to 2000 Hz. However, the usual recording frequency for most of the studies ranged from 100 to 250 Hz.

Force Platform Variables. Dynamic measurements recorded while animals walk over the plates are the primary way of using force platforms. However, measurements recorded while the animal is standing have also been used in two studies: one which used a force plate system comprised of four plates installed in a hoof-trimming chute (Mokaram Ghotoorlar et al., 2012) and the other used a combined system of force and pressure plates (van der Tol et al., 2004). Peak and average ground reaction forces (GRF) are the most important and frequent variables obtained from FPs. These have been primarily measured vertically, except in the case of 3D platforms, which can also measure longitudinal and transverse GRF. In addition to GRF, other force derivatives such as the integral of the magnitude of the GRF signatures of individual limbs with respect to frequency, ω (GRFω), and impulse have been measured. Centre of pressure (COP) is another important variable that can be measured using 3D force platforms. It was measured to identify stance phases (Skjøth et al., 2013) or to detect left and right limbs (Walker et al., 2010). Stance time is the only temporal variable that has been measured by most of the force platform systems. However, Walker et al. (2010) measured more temporal variables such as duty factor, swing time, and stride time using a 3-meter-long force platform consisting of multiple separated force plates back-to-back. They also measured walking speed and stride frequency.

The studies that used Reaction Force Detection (RFD) systems (Rajkondawar et al., 2002) – i.e., RFD system, Stepmetrix, and the redesigned 3D version of the RFD system – usually presented their measurements as Limb Movement Variables (LMV) which is typically a collection of the following variables: peak GRF, average GRF, stance time, impulse, and GRFω. The step size of individual limbs and the product of the GRF magnitude and ω integrated over frequency are the other LMVs that have been only reported once and twice, respectively. The Stepmetrix machine as a lameness detection system provides an automated locomotion scoring system (Stepmetrix locomotion scoring, SLS) using the LMVs. The SLS ranges from 1 to 100, and has been only reported in one study (Bicalho et al., 2007). Symmetry/Asymmetry measurements of some aforementioned variables such as GRF, stance time, impulse and GRFω have been also calculated by two studies (Liu et al., 2011; Thorup et al., 2014).

2.4.3.2.1.2. Pressure Mapping System (PMS)

Pressure mapping systems can serve as both an alternative and or complementary systems to FPs. They consist of a continuous network of pressure sensors which directly measure vertical pressure, surfaces, and time, allowing for force to be indirectly calculated by summation of all the sensors' pressure values. The network of pressure sensors that make up PMS allow for bi-lateral and multi-hoof measures with only a single plate. There are 19 studies that have utilized PMSs in bovine gait analysis, 16 of which used stand-alone systems and 3 which used a pressure plate laid over a built-in force plate measuring force and pressure parameters simultaneously (R. C. Carvalho et al., 2005; van der Tol et al., 2003; van der Tol et al., 2004). Pressure mapping systems usually come in the forms of plates or mats that allow for animals to walk over or stand on them. However, Oehme et al. (2019) used an insole pressure system, attaching a sensor-equipped shoe (a leather claw shoe) to the cow's left hind claw to measure kinetic variables for both standing and walking conditions.

PMSs have considerable variation in dimensions, ranging from 24.6 × 24.6 cm (I-Scan system to assess static pressure distribution of only the left hind foot) to 61 × 488 cm (Gaitwise system as a lameness detection tool). The sensor resolution of a pressure mapping system is another aspect that varies among the studies that reported it, ranging from 1.4 to 3.2 sensing elements (pressure sensors) per cm^2. Recording rate of data (frequency) is also in a great variation among the studies, ranging from 40 to 300 frames per second (Hz).

Pressure Mapping System Variables. Similar to FPs, dynamic measurements are the main method of using pressure plates among the studies, with the exception of four studies that measured pressure distribution patterns only while animals stood still on a pressure plate (Bergsten et al., 2015; Telezhenko et al., 2008; van der Tol et al., 2002; van der Tol et al., 2004). Vertical pressure, vertical GRF, impulse and stance time are common variables that can be measured by pressure mapping systems. Additionally, the pressure map provided by these systems shows the contact area and COP to investigate the force distribution amongst different zones of the hoof sole. The Gaitwise system, in addition to the mean relative force of a single hoof imprint, records the location and duration of each hoof imprint in XYT-space, all of which lead to a basic set of force-time-space variables and calculation of specific variables such as stride length, stride time, stance time, step overlap, abduction, and asymmetries. The longer length of the Gaitwise system also allows for it to measure variables of gait inconsistency across multiple consecutive steps, which increases its sensitivity and specificity for detection of mildly lame cows.

2.4.3.2.1.3. Weight Distribution Platforms (WDP)

Four-scale weight distribution platforms consist of four independent recording units (one for each limb) measuring the weight distribution between limbs while the animal is standing. These platforms have been used in 15 studies, in which they were installed either inside or outside automatic milking systems, and mainly aimed to detect leg problems as lame cows reduce weight-bearing on the affected limb, showing asymmetry in weight distribution across contralateral limbs (i.e., legs on the left vs. right side of the cow). Each recording unit typically contains 1 or 2 transducers (load cells) measuring the load applied on them. However, two studies used a weighing platform that had 4 load cells within each recording unit (Chapinal, de Passillé, et al., 2010; Chapinal & Tucker, 2012). Dimensions of recording units range from 31 ×

31 cm to 56 × 91 cm. The sizes of front and rear units are not necessarily the same, as the rear recording units installed in the milking robots are usually larger than the front units. The duration of time that a cow stands on the weighing platform for data recording varies among studies, typically ranging from 2 to 5 minutes in 1 to 4 separate measurements. The reported recording rate (frequency) varies from 1.1 to 14 recordings per seconds (Hz).

Weigh Distribution Platform Variables. Mean and standard deviation of the weight distributed between all legs or between a pair of the legs are the most frequent variables that have been measured during the recording time that animals standing on the weight distribution platform. Leg weight ratio (LWR) and weight difference (Δweight) are the other important variables associated with contralateral legs. The number and frequency of kicks and step behavior have been also calculated using weight distribution data.

2.4.3.2.2. Vision-Based technologies (VB)

Vision-based technologies involve acquiring and analyzing the motion and posture, i.e., kinematic parameters, of a walking animal using videos or sequential images. These technologies have evolved considerably from manual annotation of images and videos to automatic motion/posture optical trackers, and computer vision and machine learning algorithms. The beginning of kinematic gait analysis in cattle using vision-based technology goes back to the study of Herlin and Drevemo (1997), who measured angular patterns and hoof trajectories. Since 2000, there are 28 (34% of studies) published papers in bovine motion analysis that have utilized vision-based technology in different methods to measure locomotion variables while animals are walking through a corridor. The most frequent methods are Video analysis (VA) and Image processing (IP) techniques.

Video analysis (VA) techniques were used in 13 studies, eleven of which involved digitizing and tracking anatomical landmarks of a walking cow using motion analysis software to extract kinematic data either directly from a video (8 studies) or from consecutive still images obtained from a video (3 studies). Labelling and digitizing the anatomical landmarks can be done either manually, which requires manual localization of several points of interest, or using a marker-based system attaching reflective markers to palpable anatomical landmarks to measure kinematic data more accurately. Seven studies have employed a marker-based VA method using different types of passive markers (retroreflective markers) including reflective tape, color cardboard and reflective plastic balls. Additionally, two studies used the VA method to look at the pattern of ground contact of the claws of animals walking on a treadmill (Meyer et al., 2007; Schmid et al., 2009). All VA studies employed only a single digital camera which is usually positioned on its vertical and horizontal axis and perpendicular the plane of movement of the cows to record sagittal plane kinematics data. Therefore, they were only limited to analysis of two-dimensional (2D) kinematic data. Filming a walking cow has also been employed by a few studies to assist other technologies, i.e., force and pressure platforms and accelerometers, as a video synchronization in the determination of stride events, e.g., hoof strike, and toe off. These studies are not included under VB technologies in this review since they were not primarily used to produce gait variables.

Image processing (IP) is the other method of VB technologies that was used in 13 studies to analyze the motion and posture of a walking cow through an algorithm. After extracting still images of several desired frames from a video, some operations will be applied to the images to prepare them for the cow motion/posture recognition. Background subtraction is one of the major tasks in image processing procedure which allows an image's foreground, i.e., a moving cow, to be extracted from background for further processing. Then the motion/posture of the desired regions will be analyzed either manually or using machine learning algorithm. Studies that have employed IP techniques usually targeted one anatomical region. Back posture as one of the main lameness indicators is the most popular single target in the studies that utilized image processing technique, followed by hoof and leg movement. Similar to the videography analysis method, the image processing studies also used a side-view camera, unless in the case of using 3D camera, i.e., depth-sensing camera, to produce depth images of the cow’s back posture that is positioned overhead.

The object/target detection system is a novel technique in the field of vision-based technology and computer vision that allows us to automatically identify and locate multiple objects/targets in a video. This technique that has been used recently in one bovine gait analysis study works by applying YOLOv3 deep learning algorithm to detect the leg, head, and back regions of the cow (Wu et al., 2020). However, only leg data has been analyzed and published. Biplane high-speed fluoroscopic kinematography (HFK) is another new technique to analyze bone movement with high accuracy in a 3D approach that has been utilized in a bovine study to evaluate the range of motion of interphalangeal joints (Weiss et al., 2019).

Type of cameras vary among all the VB studies from a digital video camera to 3D depth sensors and dome cameras with various recording rates ranging from 15 to 60 fps. A high recording rate of 500 fps was set for the HFK study (Weiss et al., 2019) as well as for two studies that walked the animals on a treadmill for video analysis (Meyer et al., 2007; Schmid et al., 2009). In most of the studies it has also been stated that camera placement was set up in a position to allow researchers evaluating at least two consecutive strides.

Vision-Based technology Variables. Vision-based technologies can provide distance (spatial) and time (temporal) parameters, angular range of motion (ROM) of joints, displacement, and velocities, all of which are classified under kinematic variables. Since video analysis techniques allow researchers to quantify motion and posture of multiple anatomical regions at the same time – i.e., several points (usually major joints) on fore and rear limbs, back posture, and head position – so a more complete set of kinematic variables can be obtained. Stride length and stride time are the most frequent variables that have been measured using VA technique, followed by maximum stride height, hoof velocity, stance time, swing time, triple support, hoof overlap and ROM of fetlock joint.

On the other hand, most of the studies that used image processing methods generally focused on one specific anatomical area leading to a particular variable. There are 7 IP studies that have focused only on the back posture and provided particular variables such as curvature angles (curvature angle of back around shoulders, curvature angle of back around hip joints, overall back curvature angle, curvature distance of shoulder and hip), back posture measure (BPM) and inverse radius. In addition to back curvature, Jabbar et al. (2017) also looked at the hook bones in order to track the hind limb symmetry movements. There are two other studies that only looked at the hoof displacements and measured hoof location trackway, i.e., hoof overlap (Pluk et al., 2010; Song et al., 2008).

Leg swing/movement has been another target for the kinematic studies using vision-based technologies. Pluk et al. (2012) evaluated ROM of leg’s touch and release angles and Zhao et al. (2018) analyzed leg swing to generate six features referring to the gait asymmetry, speed, tracking up, stance time, stride length, and tenderness. Also, (Wu et al., 2020) adopted an object detection system (YOLOv3 algorithm) to detect leg movement and measured the relative step size characteristic vector.

2.4.3.2.3. Accelerometers

Gait analysis in cattle has also been done using accelerometers which are attached to the cow's leg to measure acceleration data. The output from accelerometers in bovine studies are generally classified as either behavior measures, including step activity, lying, and standing behaviors or as gait measures, including kinematics and kinetics of a gait cycle and symmetry between the legs. The current review focuses only on the gait measurement aspects of using accelerometers. There are 12 studies that have utilized these wearable sensors, i.e., 3D accelerometers, to measure gait variables. The typical location for attaching the accelerometer is above the fetlock joint at the metatarsal/metacarpal level of a limb. However, 2 studies placed accelerometer at thoracic vertebrae level in addition to the leg ones.

The main objective of using an accelerometer is to detect a lame cow or to find a gait abnormality after causing or removing it in intervention studies. The number of accelerometers per cows depends on the research set-up and the purposes. Studies that used only one accelerometer per cow, i.e., attached to one of the hind limbs or the affected (lame) limb, looked at the consistency/inconsistency of a variable within an animal or the differences between animals. In cases where more than one accelerometer per animal was used, accelerometers were worn on 2 limbs (hind limbs only or one side of the cow) or all 4 limbs, to study differences in acceleration data between the limbs.

The sampling rate of the accelerometer varies among the studies, ranging from 10 to 400 Hz. It stands to reason that the studies which employed accelerometers with high sampling rates (more than 100 Hz) could provide more details on events and moments of a gait cycle.

Accelerometer Variables. Measuring asymmetries and differences of acceleration data across the legs is one of the main parameters in the studies which employed more than one accelerometer per cow. Acceleration data has also been used to extrapolate kinematic and kinetic variables. Studies that used low frequency (less than 40 Hz) accelerometers have estimated stride time, stride length and walking speed in addition to behavioral measurements, while accelerometers with higher sampling rates have measured more detailed parameters of a gait cycle including stance and swing duration as temporal kinematic outcomes and foot-load, heel-off, and toe-off as kinetic outcomes.

2.4.3.3. Gait technology trends

The trend of technology use in bovine gait analysis has changed throughout the last two decades (Figure 2.4.4). The use of both FP and PMS was the starting point of gait analysis research in bovine between 2000 and 2004, while the use of IP techniques of vision-based technologies and accelerometers have grown considerably over the last decade and have surpassed the other technologies.

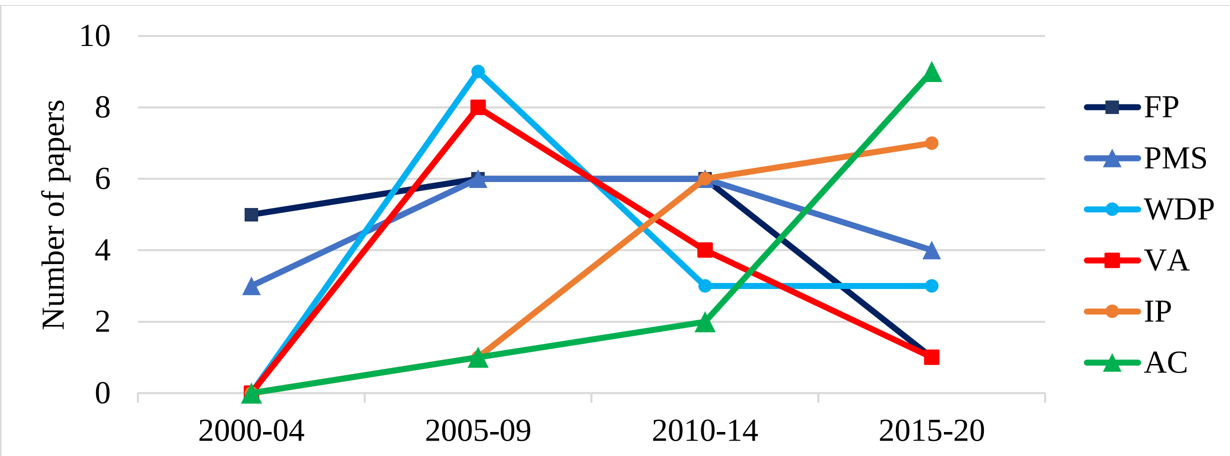

Figure 2.4.4. Technology trends in bovine gait analysis plotted in 5-year bins from 2000–2020. Force platforms (FP), pressure mapping system (PMS), weight distribution platforms (WDP), video analysis (VA), image processing (IP), accelerometer (AC).

2.5. DISCUSSION

The field of bovine gait analysis stems from equine gait analysis and human movement research, adapting technologies that initially were developed in horses or humans such as force and pressure platforms, video analysis techniques, and wearable sensors. Theoretically, the research on equine locomotion can be easily applied to cows, since both species are considered large quadrupeds with many similarities in locomotion traits. Our review was able to include a total of 82 published papers related to objective gait analysis in bovine studies, compared to 510 papers (432 papers with the same period, between 2000 and 2018) included in a review with the same scope in equine gait analysis literature (Egan et al., 2019). This confirms that gait analysis in bovine research and practice is less covered comparing to equine. The current main roles of the horse as a sport and leisure animal and the importance of its locomotor system performance can probably explain the difference (Lesimple, 2020). Moreover, equine quantitative gait analysis is not only limited to lameness studies; there are many other practical uses in clinics and training centers with the goal of improving equine performance, optimizing training, and enhancing the horse-rider relationship (Egan et al., 2019; Gómez Álvarez & van Weeren, 2019). In cows, however, as a livestock animal, lameness and identifying impaired locomotion remains the primary topics investigated using gait analysis technologies. Indeed, lameness is an important issue in dairy cattle and is one of top 3 reasons for involuntary culling cows in North-America (Booth et al., 2004), and the use of automated technologies for early detection and prevention is a main focus of interest. The results of this review also confirm that lameness detection is the main purpose of gait analysis research on cows (55% of studies) and the efforts for automatizing lameness detection on farms have influenced the research trend. Even most of the Intervention/Comparison studies looked at identifying impaired limb and gait abnormalities between different set-ups, confirming the dominance of lameness detection in gait analysis. Nevertheless, research focusing on lameness detection in dairy cattle has caused a limited number of studies on exploring natural (i.e., when cows are sound) gait/claw biomechanics using various technologies (11% of studies), especially between different breeds and size of cows, and investigating gait at early life. In fact, with regard to early life gait research, there is only one study that looked at the gait kinetics of 4-6 months old male calves. While over a third of the literature is on Intervention/Comparison studies (35.5%), the impact of other factors of welfare concerns and cow management (e.g., housing systems, stall dimensions, heat stress, outdoor access) on cow's locomotion using gait analysis technology are seldom studied. To the best of our knowledge, there is no study published on the use of gait analysis technologies in beef cattle despite the fact that lameness is also a concerning issue in beef industry (Tunstall et al., 2019).

2.5.1. Strengths and weaknesses of cow gait technologies

2.5.1.1. Force Platforms

Although force platforms (FP) are considered the gold standard because of their recognized accuracy and high frequency measurements, they do have some limitations. Force plates are usually imbedded in floor and relatively immovable. The installation procedures require a massive and costly concrete foundation. More importantly, it is challenging to measure individual footfalls when more than one foot touches the plate at the same time. Therefore, the best results are achieved when only one foot from one side of the animal fits on the plate. For this reason, force plates generally come in pairs that are set parallel to one another and most of the FP are less than 2 meters long. For the same reason, it is difficult for FP to provide the spatial variables and describe the location of the foot falls unless in case of use of multiple force plated end to end or 3D force platforms. The most common objective among the papers used FP, is lameness detection, most of which used a commercial version of FP for on-farm use (i.e., StepMetrix™, Boumatic LLC, WI, USA). The use of FP in studies dropped since 2015, suggesting that the weaknesses of FP may outweigh the strengths, especially as other technologies, by comparison to FP, are capable of measuring a more diverse assortment of variables that can more robustly analyze gait.

2.5.1.2. Pressure Mapping Systems

Unlike the FP, pressure mapping systems (PMS) can distinguish and analysis individual footprints regardless of how many feet are on the ground. As such, they can be used as a single mat or plate in different dimensions. One of the downsides of the PMS is that the peak force is generally under-measured. A study on equine kinetics showed that the pressure plates cannot be used interchangeably with a force plate to measure absolute values of limb loading (Oosterlinck et al., 2010). Nevertheless, the force measurements by pressure plates are consistent within themselves, allowing them to be used independent of other technology. As the results of the current review showed, the PMSs that were used in bovine gait studies are produced by three main manufacturers, RSscan, Tekscan and GAITRite. RSscan and Tekscan devices were mostly used in the Intervention/Comparison studies to investigate the effect of hoof trimming, local analgesics, and flooring type on cows' biomechanics. GAITRite's PMS, known as the Gaitwise system, is more suitable to identify lame cows and is the primary system used in lameness detection studies. The main differences between the Gaitwise system and the other pressure mapping systems are the output variables and the length of the mats. The Gaitwise system, in addition to force and temporal measurements, registers the position of the imprints on the mat. Also, the length of the active surface of the Gaitwise system is 488 cm while the maximum length of the other pressure plates used in bovine studies is 240 cm. The long length of the Gaitwise system makes it able to measure up to two complete gait cycles, which is a key for lameness detection studies. In comparison with FP, PMSs are more practical and efficient in terms of easy implementation and generating more diverse outcomes either in research studies or at the farm level.

2.5.1.3. Weight Distribution Platforms

While being a limitation for FP and PMS systems as well, numerous failed measurements because of placing hooves outside of the measuring zones have been reported as the primary weakness for WDP. WDP measures variables only while an animal is standing, so the outcomes are limited to static measures and no information on gait cycle kinetics can be taken. Nevertheless, the strength of WDP is the fact that it is not just a quick snapshot of the cow walking, but a longer review of how she distributes her weight. A lack of even distribution of weight makes it easier to pinpoint the limb of issue in these cows with greater certainty, as the reluctance to bear weight in this case is usually a sustained measure. Moreover, they can be easily implemented in farms with the least space occupation, such as embedded in the flooring of milking robots or cattle chute. The results of our scoping review confirm this, since WDPs are primarily used for lameness detection purposes at the farm level.

2.5.1.4. Video Analysis

Video analysis is the gold standard for kinematic measurements. They are able to provide a variety of gait variables from distances to ROM, velocities, and trajectories. They allow researchers to investigate multiple anatomical locations on the body with a single passage yielding a better understanding of different aspects of an animal locomotion. Since an impaired locomotion (lameness) can manifest in different ways, i.e., from short stride length to back arch, joint stiffness, asymmetries, etc., so a system that can consider all of these variables, can provide a more accurate analysis. However, these systems, especially marker-based VA systems, poses several limitations including marker placement error, observer (digitizer) error, and the time-consuming process of manual/semi-manual tracking. Moreover, it requires animal preparation (attaching markers on animal's body) and a specific environment (room) in terms of controlling the light conditions and providing a wide space to not blocking cameras' view of the markers. All these procedures can be challenging and make these techniques unfeasible to implement on commercial farms. The results of this review illustrated that the use of VA techniques have decreased over time, from 8 studies between 2005 and 2009 to only 1 study over the last five years.

Moreover, all the previous studies that used VA technology were limited only to 2D kinematic analysis which includes several limitations by comparison to three-dimensional (3D), where multiple synchronized cameras are being used. Some of these limitations include parallax error and perspective error that occur when subjects move away from the optical axis of the camera and subjects are restricted to movement within the plane of calibration and accuracy is compromised. Also, 2D angular data are limited to one degree of freedom (DOF) for joint rotation within the sagittal plane, while 3D kinematic data allow the researcher to explore the full range of motion (ROM) and orientation of segments and joints within 3D space (St George, 2017). Therefore, although the use of VA techniques is challenging, the high accuracy of these systems, especially the 3D video analysis systems, makes them a reliable reference for the future works of using marker-less VA technologies.

2.5.1.5. Image Processing

By comparison to VA systems, the downside of the IP methods is that, since they usually focus on one anatomical region as a lameness indicator, their outcomes are limited to the targeted region and the other facets of lameness will be missed. However, use of machine learning algorithm and eliminating the requirement of animal preparation (e.g., with reflective markers) allows them to be utilized as automated systems on commercial farms. Also, the use of overhead 3D depth image cameras instead of the side-view digital cameras benefited this technology to overcome the challenges of side-view image capturing at farm conditions, including occlusions and sensitivity to lighting variance in order to facilitate the image segmentation of the foreground from the background. Our results showed that efforts for implementing IP technology as automated lameness detection systems on farms has become more prevalent in gait analysis studies over the last decade (13 studies between 2010 and 2020).

2.5.1.6. Accelerometers

Accelerometers have been used as a technology for gait analysis in cattle studies since 2009 and have been the most widely used technology in the last 5 years. Previous studies showed that pedometers (accelerometers) can be a promising tool for detecting lameness and foot pathologies in dairy cows. Uncontrolled walking speed and cow traffic as well as behavior are the usual limitations reported for gait analysis using FP, PMS and WDP and vision-based technologies, but not for accelerometers. Accelerometer outcomes are not dependent to a single passage or a specific walking corridor. At present, however, accelerometers still carry limitation. For example, not all variables can be measured using a single pedometer, with useful gait metrics for detecting impaired gait, such as asymmetry of acceleration between legs, requiring 2 or more devices. Technologies that require more hardware can be a barrier to adoption on commercial farms (O'Leary et al., 2020). Moreover, current pedometers used on farm generally have lower data sampling rates as they are less costly than high-frequency pedometers; however, this trade-off can compromise the efficacy of the pedometer use for detecting impaired gait. Low frequency accelerometers can make gait analysis more challenging and requires more research.

2.5.2. Technology adoption

The adoption of the technologies for gait analysis depends on the user needs. Among automated lameness detection systems in dairy cattle a sensor attached to the cow was preferred by farmers, followed by a walkover system and a camera system (Van De Gucht et al., 2017). Another limitation of the adoption is the accuracy of the technology. The accuracy of these technologies have been discussed in details by Alsaaod et al. (2019).

2.6. CONCLUSION

A strong demand for automatic lameness detection influences the path of development for quantitative gait analysis technologies in bovine. Force and pressure platforms, image processing techniques, and accelerometers have shown that they are capable and practical methods for automated lameness detection systems, despite their weaknesses. Computer vision technologies using deep learning and wearable sensors (accelerometers) as novel and promising technologies would be the next stage of quantitative gait analysis in bovine. Although the field of bovine gait analysis has evolved considerably through the last two decades, more research is needed to achieve more accurate, practical, and user-friendly technologies for research and on-farm applications.

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CONNECTING TEXT

In chapter 2, we reviewed the available literature through a systematic scoping review to explore technologies used for direct cow gait analysis over the last two decades. We mapped the research trends and reviewed the gait variables generated by these technologies. We classified gait analysis technologies into three main categories: Force and Pressure platforms, Vision-based technologies, and Accelerometers. Thematic analysis of research aims showed that lameness detection was the most frequent research aim targeted by studies that employed gait technologies. Our scoping review also highlighted the gaps in the current literature. Generally, when compared to a similar scoping review in equine, quantitative gait analysis in cows was found to be notably less researched, even though gait technologies can be interchangeably used in both species due to their similarities in locomotion traits. Only a few studies are available to investigate cow biomechanical gait differences across the breeds and sizes of cows and early life, and none was touching on gait analysis using technology in beef cattle. In addition, there is little research to examine the impact of different housing systems (with various facilities and management) and other welfare concerns on gait abnormalities with the assist of technology.

Chapter 3 describes an experimental study where the goal was to examine the effect of daily access to outdoor on gait and hoof health of lactating cows housed in tie-stalls. To achieve this goal, 1 hour per day access to an outdoor exercise yard for five weeks was provided for the cows grouped in the Exercise group, while our control group (Non-exercise cows) remained indoors. Cow step activity was continuously recorded via pedometers to confirm changes in the level of locomotor activity. Cow gait was assessed using a visual numerical rating system (NRS). Hoof health was also evaluated by clinical assessment of claw lesions and hoof surface thermography. This experiment will give an idea of the negative or positive impact of partial outdoor access (with the level of 1h/d, 5d/wk) on gait changes and hoof health of long-term confined cows in a tie-stall barn.

CHAPTER 3 - HOW DOES 1 HOUR DAILY OUTDOOR ACCESS AFFECT THE GAIT AND HOOF HEALTH OF TIE-STALL-HOUSED LACTATING DAIRY COWS?

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3.1. ABSTRACT

Hoof and leg health issues are prevalent in the dairy industry and is a welfare concern. Previous studies showed that increasing movement opportunity through pasture access could improve gait and hoof health in stall-based systems. However, most of these studies were conducted in free-stalls and little research has been carried out to directly evaluate the effects of outdoor access on gait and hoof health of cows housed in tie-stalls. The objective of this experiment study is to evaluate how regular access to an outdoor exercise yard affects gait and hoof health of lactating Holstein cows housed in tie-stalls.

Thirty cows were enrolled in the study and blocked by parity and DIM (n=6/block). Within each block, cows were evenly assigned to one of two treatments: Exercise (cows receiving outdoor access, i.e., 1 h/d, 5d/wk for five weeks) and Non-Exercise (cows remaining indoors for the same duration of the trial). Cow gait was assessed using a visual numerical rating system (NRS) comprising of an overall NRS score and 6 gait attributes at three data collection periods: before the start of the study (Pre-trial), at the end of the study (Post-trial), and 8 weeks after the end of the experiment (Follow-up). Hoof health was evaluated by claw lesion assessment and hoof surface thermography. The number, location and severity score of claw lesions were recorded at Pre-trial and Follow-up. Hoof thermography was conducted using 2 different methods, original image analysis and normalized image analysis, at week 1 and week 5 of the trial. Also, to confirm the changes in the level of activity after having access to outdoor, step activity was continuously recorded during the trial using pedometers.

Results showed that the level of step activity did not differ between treatment groups throughout the trial. However, Exercise cows tended to express a higher number of steps than Non-Exercise cows (705 ± 71.4 vs 518 ± 67.9 steps/d, respectively, $P = 0.07$). There was no statistically significant difference between treatment groups and periods for the changes in the overall gait score and the six gait attributes ($P > 0.05$). Sole hemorrhage was the only claw disorder observed. The prevalence of claw lesions did not change for both Exercise (7.50% to 6.67%; $p = 0.58$) and Non-Exercise cows (10% to 8.04%; $P = 0.16$) from Pre-trial to Follow-up. Similarly, there was no impact of time or treatment groups on the severity of claw lesions ($P > 0.05$). Original thermal image analysis resulted in no significant alteration in hoof temperature between treatment groups and times ($P > 0.05$). One statistic feature, Kurtosis obtained from normalized image analysis, differed significantly between treatment groups and weeks ($P < 0.0001$). These results suggest that 1h daily access to outdoor neither increase step activity nor improve gait score of cows housed in tie-stall. However, claw lesions and hoof thermography results suggest that daily outdoor access can be provided to tie-stall cows without adversely affecting the hoof health. Further research is needed to determine if providing different types or levels of outdoor access can be used to benefit hoof and leg health.

3.2. INTRODUCTION

Despite growing welfare concerns regarding the long-term confinement of farm animals (Robbins et al., 2019), tie-stall housing makes up a considerable proportion of housing systems found on dairy farms in Canada (73%), particularly in Quebec (91%; CDIC, 2020). Tie-stall housing could be considered the most restrictive housing systems for dairy cows movement (Shepley, Lensink, & Vasseur, 2020). A tethered cow housed in a tie-stall barn is restricted in voluntary movement and social and natural behavior (Popescu et al., 2013). Although switching from a tie-stall system to an alternate dairy housing system is not easy, other housing and management solutions may be able to alleviate this restriction and provide more movement opportunity. It has been shown that adding access to additional space to existing indoor housing systems, i.e., pasture or an outdoor exercise yard, which can result in greater locomotor activity, could improve a cow's health and welfare (Gustafson, 1993; Popescu et al., 2013; Shepley, Lensink, & Vasseur, 2020).

Lameness is one of the most serious welfare concerns in the dairy industry (Whay et al., 2003), and has been reported in epidemiological studies to affect 20 to 55% of indoor-housed dairy cows in North America (Solano et al., 2015; von Keyserlingk et al., 2012). Previous studies suggest that stall-based systems with access to pasture have lower risk of lameness (Chapinal et al., 2013; Hernandez-Mendo et al., 2007; Hund et al., 2019). However, most of these studies have been conducted in free-stalls and little research has been carried out to directly evaluate the effects of outdoor access on gait and hoof health of cows housed in tie-stalls.

Claw lesions are the main cause of lameness in dairy cattle and they are basically classified as infectious disorders (e.g., digital dermatitis, interdigital dermatitis, and interdigital necrobacillosis) and non-infectious disorders i.e., laminitis related disorders (e.g., sole hemorrhage, sole ulcer, white line disease (Egger-Danner et al., 2014; Murray et al., 1996). Since several weeks may be required for a lesion to become visible on the sole of the hoof (Shearer et al., 2015), we employed an infrared thermography camera to monitor short-term effects of outdoor treatment on cow's hoof temperature. Previous studies showed that hoof surface thermography has the ability to detect increased temperature generated by claw lesions including non-infectious lesions, and infectious lesions (Gianesella et al., 2018; Harris-Bridge et al., 2018; Nikkhah et al., 2005; Stokes et al., 2012). It is also shown that hoof thermography can be used for early detection of lesions at least 6 weeks before clinical onset (Wood et al., 2015).

The objective of this study is to evaluate how regular access to an outdoor exercise yard affects gait, measured using a visual numeric rating system, and hoof health, measured by clinical hoof assessment and hoof surface thermography, of lactating cows housed in tie-stalls. We also seek to confirm the changes in the level of activity when cows are provided with access to outdoor through pedometer-recorded step activity. We hypothesize that cows with outdoor opportunity will show a larger number of average daily steps and consequently, we expected that the NRS score and the 6 gait attributes would show improvements after a 5-week period of daily outdoor access compared to cows that receive no outdoor access. Furthermore, we hypothesize that outdoor access will not lead to any detrimental effects of outdoor access on hoof health – measured based on prevalence and/or severity of claw lesions and hoof surface temperatures.

3.3. MATERIALS AND METHODS

3.3.1. Ethics Statement

A certified Animal Care Committee of McGill University and Affiliated Hospitals Research Institutes reviewed and approved the use of animals in this project and all procedures (#2016-7794). All aspects of this study meet the high standards established by the Canadian Council on Animal Care to ensure the continued humane and ethical use of animals in research.

3.3.2. Study Design

Thirty tie-stall-housed lactating Holstein cows were enrolled in the study and grouped into five blocks by parity and DIM (n=/block). Within each block, three cows were randomly assigned to the Exercise (cows receiving outdoor access; n = 15) and three to the Non-Exercise treatment (cows remaining indoors for the duration of the trial; n = 15). All 30 cows were located into 4 adjacent rows in the barn (Figure 3.3.1). To facilitate moving the Exercise cows to outdoor exercise yard, they were located in rows 3 and 4 near the exit door. Outdoor access for Exercise cows was provided for 1 h/d, 5d/wk, i.e., Monday to Friday, for five weeks. Exercise cows from each group were moved to one of five randomly assigned outdoor exercise paddocks measuring 117 m^2 (9 m x 13 m) each, located in a pasture-based exercise yard adjacent to the tie-stall barn. Exercise paddock assignment was rotated clockwise for each group weekly to ensure the cows experienced all five paddocks with limited change in neighboring cows for the duration of the study. Four main measures - step activity, gait scoring, claw lesion assessment, and hoof thermography - were assessed at different periods during the study. Figure 3.3.2 shows the timeline of the study.

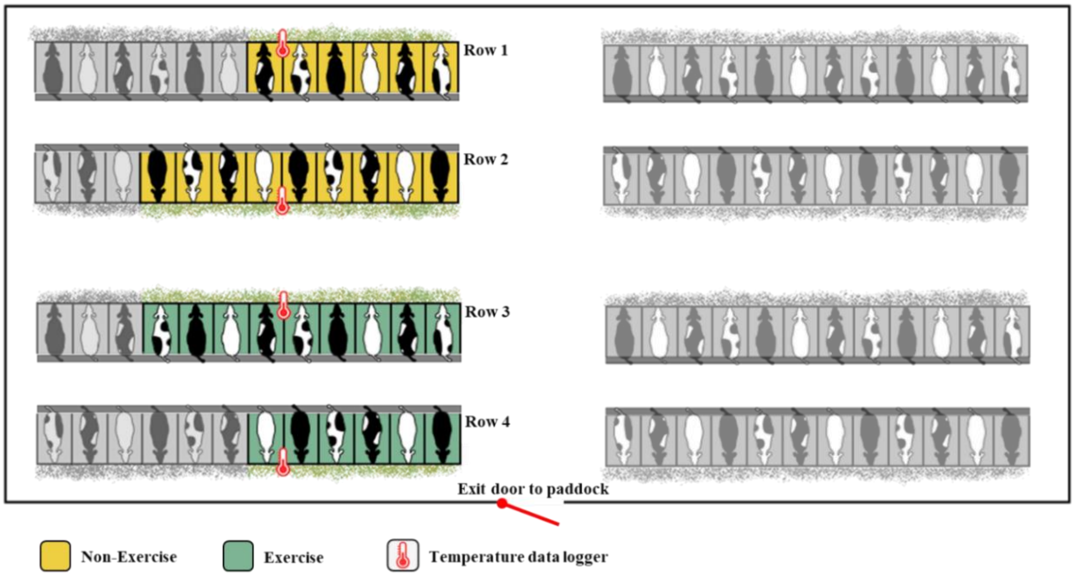

Figure **3.3.1.** An overview map of how the research cows were located in the tie-stall barn across adjacent rows. Non-Exercise cows (yellow) were housed in rows 1 and 2. Exercise cows (green) were housed in rows 3 and 4 close to the exit door to the outdoor exercise yard. Four temperature data loggers were installed at the center of each row 2.5 m from the ground for thermography purposes.

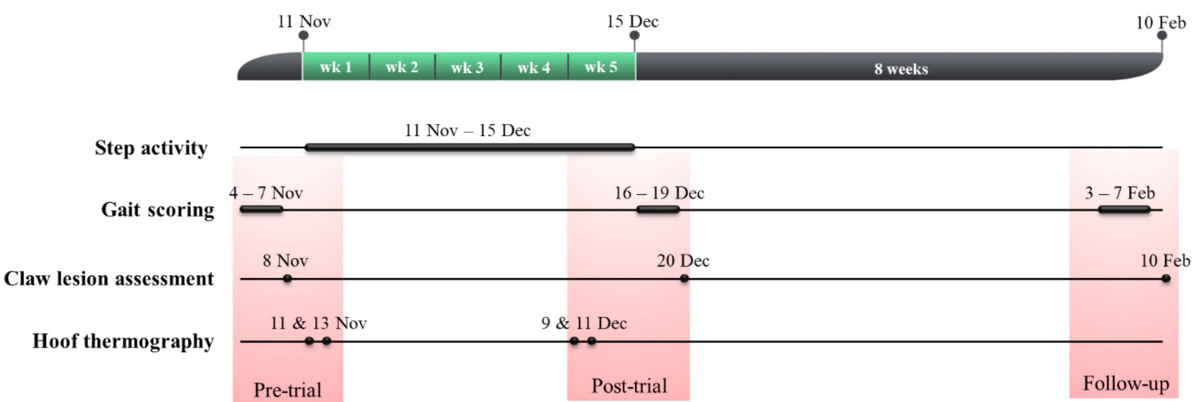

Figure 3.3.2. Timeline of the study illustrating the periods of data collection during the 5 weeks of trial (green color) from 11 Nov to 15 Dec 2019 and the weeks before and after the trial. Step activity was recorded continuously during the trial (from 11 Nov to 15 Dec). Gait scoring was conducted at 3 periods: the week before the trial (4-7 Nov), the week immediately after the trial (16-19 Dec), and the 8th week after the trial (3-7 Feb). Claw lesion assessment was conducted at three times: before the trial (8 Nov), immediately after the trial (20 Dec), and 8 weeks after the end of trial (10 Feb). Hoof thermography was recorded within week 1 (11 & 13 Nov) and week 5 (9 & 11 Dec) of the trial.

3.3.3. Step Activity

Step activity was recorded continuously throughout the five weeks of the experiment using a 3D pedometer (IceTag™, IceRobotics, Edinburgh, Scotland) attached on the left or right rear leg of the cow (Shepley et al., 2017). Pedometer data was retrieved weekly using the IceManager software (IceManager, IceRobotics, South Queensferry, UK). Data was output in 1-min intervals and presented as the average daily number of steps, based on the summation of daily activity averaged across 7 days each week.

3.3.4. Gait Scoring

Due to the restrictive timeline, a subsample of 20 cows out of 30 (4 cows from each block) were randomly selected for gait analysis at the three data collection periods (Pre-trial, Post-trial, Follow-up). Cows were removed from their stalls and led by halter to a designated experimental area. A test track containing a straight test corridor measuring 1.8 m wide by 8.1 m long was created in the experimental area. A high-speed camera (60 fps, 720 resolution, normal view; GoPro Hero 4, GoPro, Inc., San Mateo, California, USA) perpendicular to the corridor, 2.4 m from the corridor center, recorded the passages. Cows were walked in the experimental area following handling protocols detailed in Shepley and Vasseur (2021b). Cows were walked for a minimum of 5 passages along the test corridor, ensuring that the cow was walking at a consistent pace without running and stopping for at least one passage. Grain, placed at least 1 m in front of the cow, and/or an additional handler, positioned behind the cow at the point of balance, were used as needed to encourage movement of the cow. Cows displaying poor behavior in the experimental area were excluded, yielding 15 cows (9 Exercise and 6 Non-Exercise cows) enrolled in gait analysis.

Forty-five recorded videos (15 cows at three data collection periods) were used for gait scoring, which was conducted by a trained observer. All videos were coded with numbers and randomized so that the observer was unaware of the animals' treatment group and the data collection period. Six gait behaviors were scored from video: swinging out, back arch, tracking-up, joint flexion, asymmetric gait, and reluctance to bear weight (Table 3.3.1), described by Shepley and Vasseur (2021b). Scores were assigned on a 0-5 scale with 0.5 intervals, with 0 indicating the soundest score for the gait behavior and 5 indicting the worst. An overall gait score was also assigned, based on the 1-5 numeric rating scale (NRS) with 0.5 intervals described by Flower and Weary (2006), with 1 indicating the soundest gait and 5 indicating severe lameness. Gait was analyzed as the change of gait scores for each gait variable between Post-trial and Pre-trial and between Follow-up and Pre-trial.

Table 3.3.1. Description of visual gait variables and the corresponding scoring 0-5 scale where 0 indicates the best possible visual appearance for a gait variable and 5 is the worst; described by Shepley and Vasseur (2021b), adapted from Flower and Weary (2006).

Gait Measure	Definition	Scoring Scale with 0.5 intervals	
		0	**5**
Swinging out	The degree to which the hind leg moves side to side when walking	Hind legs moving in straight line during the swing phase	Pronounced, circular motion of the hind legs during the swing phase
Arch back	The shape of the spine when the cattle walks	Flat spine	Convex arch between the withers and tailbone
Tracking up	It is the gap between the imprint left behind the front hoof and the new imprint formed from the rear hoof	Hind hoof falls in imprint left by the front hoof of the same side	Hind hoof falls short of the imprint left by the front hoof of the same side
Joint flexion	Related to the flexes and extensions of the limb while the cow is moving	All limbs flex and extend easily	All limbs are stiff and limited in their range of motion
Asymmetric step	How even the stepping pattern of a cow is	Equal steps: cow places her hooves in an even "1, 2, 3, 4" rhythm	Not equal; cow places her hooves in an uneven rhythm
Reluctance to bear weight	How evenly the cow distributes her weight when walking	Bears weight equally over all legs	Uneven weight bearing between legs

3.3.5. Claw Lesion Assessment

Clinical assessment of hooves was conducted when cows were restrained in a tilt hoof trimming chute before the start of the study (Pre-trial), at the end of the study (Post-trial), and 8 weeks after the end of the experiment (Follow-up). A full hoof trimming was done at the pre-rial and Follow-up periods while only a sliver of horn was trimmed at the Post-trial to examine the possible penetration of the sole by foreign bodies. The data recorded at Post-trial were not included for further analysis due to the time-dependent process of laminitis pathogenesis, wherein the effect of metabolic and mechanically induced conditions take eight weeks to become visible on the sole of the hoof (Shearer et al., 2015). Therefore, only data recorded at Pre-trial and Follow-up periods were analyzed. The number and location of claw lesions were recorded by an experienced observer using a recording sheet that indicated the cow's claw specific anatomical zones (Figure 3.3.3) adapted from Shearer et al. (2004). The recorded lesions were classified and named based on ICAR Claw Health Atlas (Egger-Danner et al., 2014). Additionally, the severity of the lesion of all 8 claws of each cow (i.e., medial and lateral claws of 2 front and 2 hind hooves) were scored on a 5-point scale (Figure 3.3.4), which combined scoring systems from Flower and Weary (2006) and Nikkhah et al. (2005). In the adapted scale, 0 represented no hemorrhages or discoloration; 1 represented slight hemorrhages; 2 represented a moderate hemorrhagic lesion; 3 represented a severe hemorrhagic lesion and possibly fresh blood, and 4 represented a sole ulcer (exposed corium). During hoof trimming, digital photos of the sole of all the hooves were taken using the rear camera of a smart phone to be double checked by the same observer for final confirmation of the lesion scores.

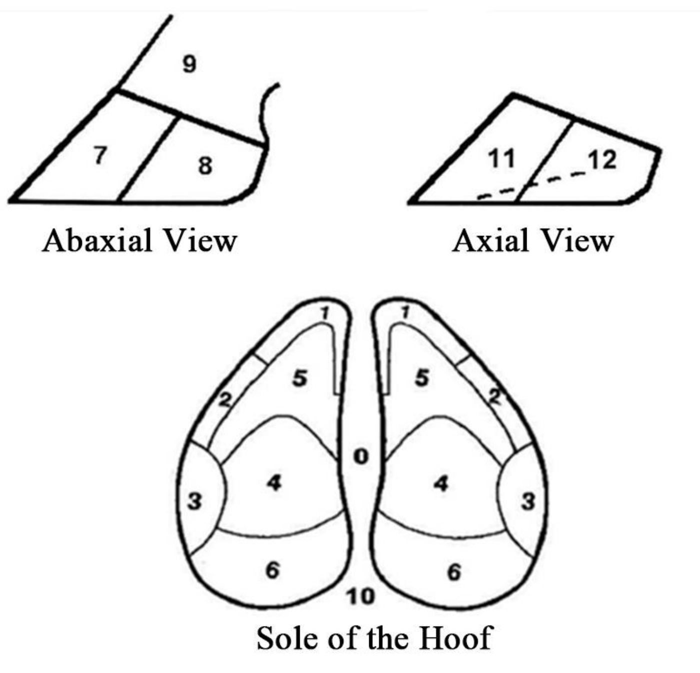

Figure 3.3.3. Claw diagram that illustrates 12 anatomical zones used in recording claw lesions. Adapted from Shearer et al. (2004).

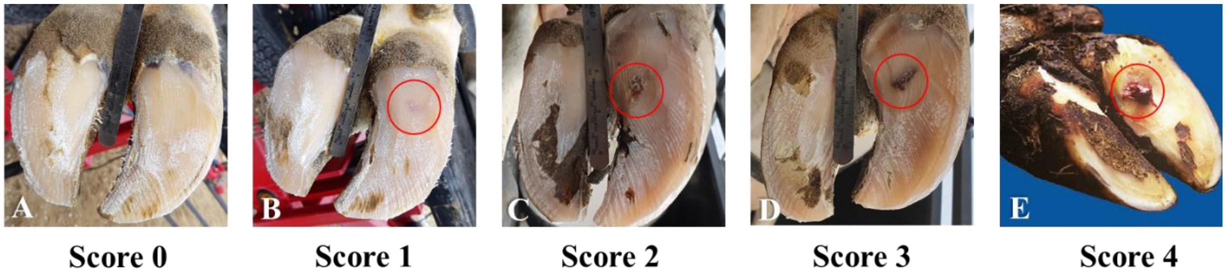

Figure 3.3.4. Five-point scale scoring system for claw lesion severity, starting from score 0 = No lesion (photo A) to Score 4 = sole ulcer (exposed corium, photo E); adapted from Nikkhah et al. (2005) and Flower and Weary (2006). Photos A to D were taken by Nejati during data collection. Photo E is a courtesy of ICAR Claw Health Atlas.

3.3.6. Hoof Thermography

Thermal images were taken from the dorsal view of each of the four feet of all 30 cows enrolled in the study twice a week (Monday and Thursday) for the entire period of the trial (five weeks). However, only the images taken at the first (Pre-trial) and fifth (Post-trial) weeks were analyzed for the current study (Figure 3.3.2). All thermal images were taken between 8:00 AM and 9:00 AM while cows were standing in their stalls. All cows were required to stand at least 10 minutes before taking images. Stall positions of cows were constant throughout the trial. All images were taken in an enclosed barn away from wind and direct sunlight. Nevertheless, to consider the possible ambient temperature variation during the trial (different rows of stall location and different days) in our analysis, ambient temperature at the center of each row (Figure 3.3.1) was recorded using temperature data loggers (Onset HOBO® MX2300 Temperature/RH Data Loggers, Onset Computer Corporation, Bourne, Massachusetts, USA). The average ambient temperature of each row 1 hour before image capture (7:00 AM) until the end of image capture (9:00 AM) was then calculated. Ambient temperature ranged from 9.4 to 13.9°C across the trial.

A FLIR E4 upgraded to E8 firmware infra-red thermal imaging camera (IRC) was used to take the thermal images. The IRC also generated a digital photo of the same frame as well as the thermal image. The object temperature range of the IRC was –20°C to 250°C with a thermal sensitivity of 0.06°C and an accuracy of ± 2% of reading in this restricted range. The wide-angle lens was 45° × 34° and the IR resolution was 320 × 240 pixels. Before taking images, object parameters were adjusted on the camera as follows: emissivity value, 0.98; distance from object, 1 m; and reflected temperature, 20°C.

Images of all four feet were taken from the dorsal view from a distance of approximately 1 m. Consistency of camera distance at the time of image capture was ensured through use of a custom-made stick which was attached to the camera and positioned between the camera and foot. Because the stall cleanliness was maintained feet were generally in good hygiene condition, all thermographic images were obtained without any preparations (i.e., washing or cleaning). Nevertheless, the digital format of images taken by the thermal camera were used to evaluate the foot hygiene (hoof, coronary band and dew claws area) using a 4-point hygiene scoring system ranging from 0 to 3 (Figure 3.3.5), where 0 represents a completely clean foot, 1 represents a slightly dirty foot (lightly scattered splashes of manure) 2 represents a moderately dirty foot (hoof and coronary band area are mostly covered with dirt or manure, and 3 represents a very dirty foot (completely covered with dirt or manure) (Schreiner & Ruegg, 2003). Feet with scores 2 and 3 were dropped from further analysis.

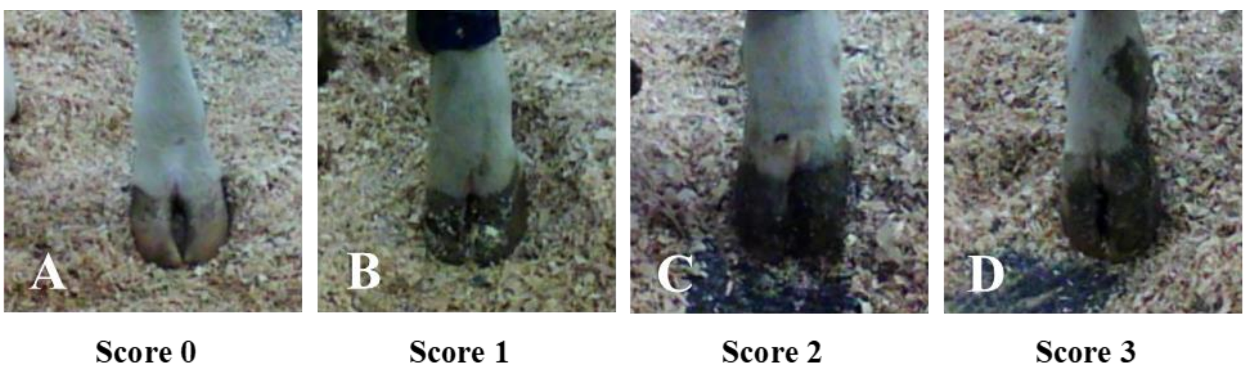

Figure 3.3.5. Four-point scale foot hygiene scoring system where 0 indicates an entirely clean foot (photo A) and 3 is a foot covered with dirt (photo D); adapted from Schreiner and Ruegg (2003).

Thermal image analysis was done using two methods: 1- original image analysis and, 2- normalized image analysis. The first method involves extracting temperature parameters directly from the original thermal images using Therma-CAM Researcher Professional 2.10 software (FLIR Systems, Inc., Wilsonville, Oregon, USA). After importing images into the software, two regions of interest (ROI) including the coronary band (CB) area and a control skin area above the CB were selected using analysis tools (Figure 3.3.6). Then four thermal variables were extracted from the two ROIs for further analysis including CB maximum temperature (CB-Max), CB mean temperature (CB-Mean), CB standard deviation (CB-STD), and temperature difference (ΔT) between CB-Max and mean temperature of skin control area. The ΔT was calculated to consider the within-animal temperature difference rather than absolute values (Alsaaod & Büscher, 2012; Nikkhah et al., 2005).

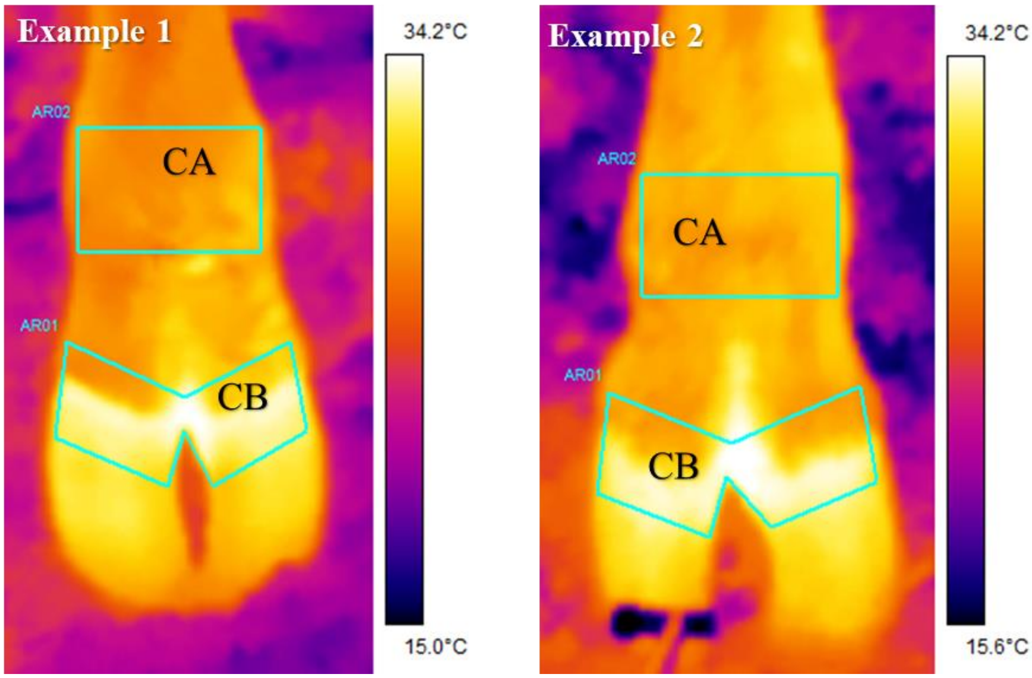

Figure 3.3.6. Two examples of how the region of interests (ROI) were selected. Control Area (CA) is a fit rectangular of skin with a narrow safe margin from the foot edge at the level of dew claws. Coronary Band (CB) is an area above the hoof wall where the hair coat is sparse and can be clearly identified in thermal images (the warmest line) with 1 cm margin from above and below.

Since foot surface temperature changes with the variation of the ambient temperature (Alsaaod & Büscher, 2012; Stokes et al., 2012), the second method (Normalized image analysis) was done to reduce the effect of ambient temperature (Lu et al., 2011). This method consists of image pre-processing and data extraction using MATLAB (Supplementary Figure 3.7.1, R2021a, Mathworks Inc., Natick, MA, USA). The image pre-processing (Figure 3.3.7) includes cropping a square area where the coronary band is located at the bottom one third of the square and the top two third is the skin above the CB, conversion to greyscale, conversion to double precision, and pixel normalization to a scale of 0 -1. Four common statistical features including mean, standard deviation (STD), skewness, and kurtosis (Table 3.3.2) were extracted from each processed image.

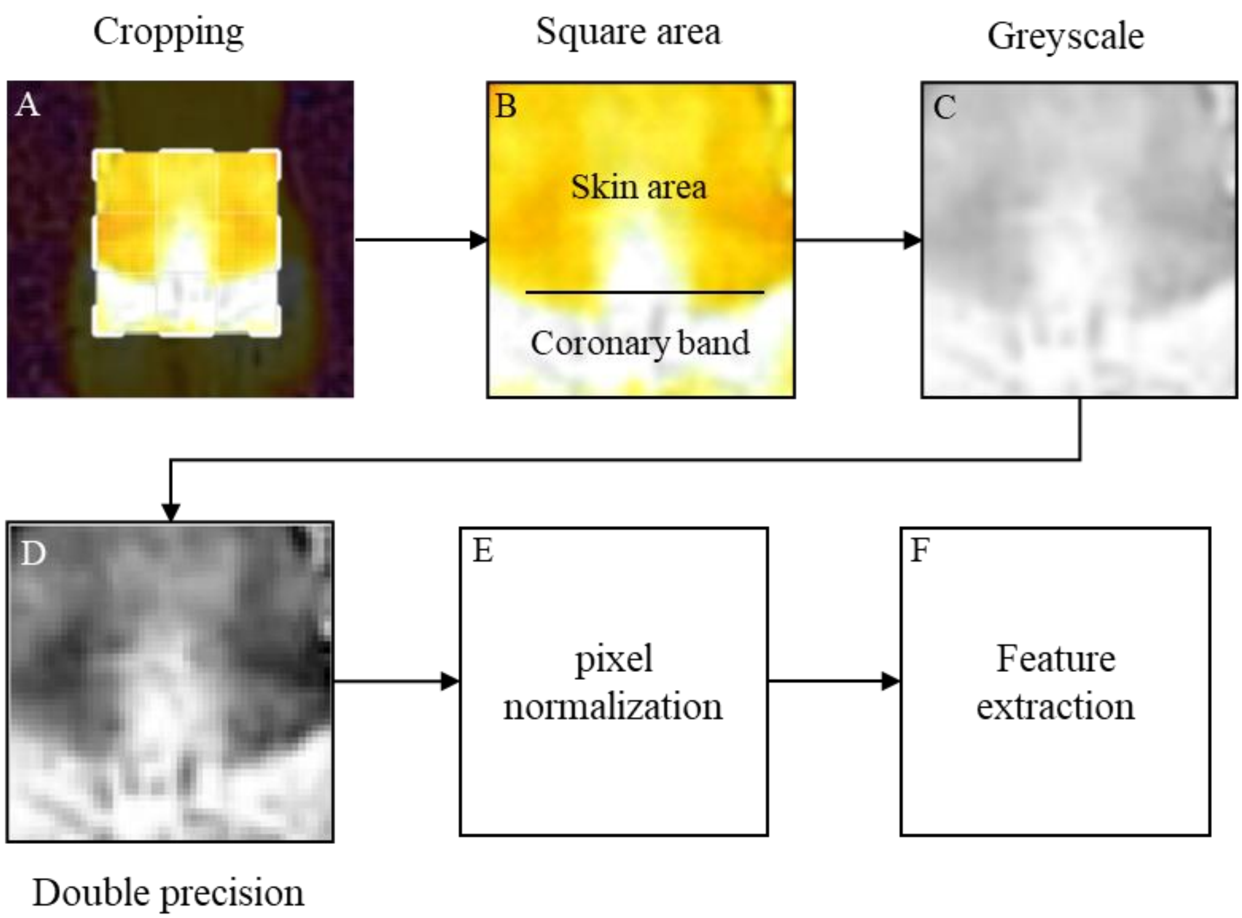

Figure 3.3.7. Normalized image analysis and its various pre-processing stages including segmenting a square area (A) consisting of the coronary band and the skin area (B), conversion to greyscale (C) and double precision (D), pixel normalization (E), and statistical features extraction (F).

Table 3.3.2. Definition and equation of four statistical features (mean, standard deviation, skewness, and kurtosis) that were calculated for each thermal image using normalized image analysis, as described by Al-Obaidy (2016).

Statistical feature	Definition and Equation
Mean	The mean measures the average value of the intensity values. If the mean is high, then it means that the image is bright and if low, then the image is dark. $$mean = \sum_{i=1}^{L} i.P(i)$$
Standard deviation (STD)	The standard deviation shows the contrast of gray level intensities. The low value of the standard deviation indicates low contrast, and the high value shows the high contrast of the image. $$STD = \sqrt{\sum_{i=1}^{L} (i - mean)^2.P(i)}$$
Skewness	It is the measurement of the inequality of the intensity level distribution about the mean. The value will be positive or negative of the skewness. Negative value shows that the large number of intensity values is on the right side of the mean. Positive value shows that many intensity values are on the left side of the mean. Zero value indicates that distribute the intensity values is relatively equal on both sides of the mean. $$skewness = \frac{1}{std^3}\sqrt{\sum_{i=1}^{L} (i - mean)^3.P(i)}$$
Kurtosis	It is used to measure the flatness of the thermal distribution for each region. Lower kurtosis shows that the temperature distribution within the region is homogenous. The higher value of the kurtosis shows that the peak of the distribution is sharp, and the tail is longer and fatter. $$kurtosis = \frac{1}{std^4}\sqrt{\sum_{i=1}^{L} (i - mean)^4.P(i)}$$

3.3.7. Statistical Analysis

Statistical analysis was conducted using R (R Core Team, 2021) and its specific packages. Using the package *nlme* (Pinheiro et al., 2021), the following mixed-effect statistical model was used to analyze step activity data

$$Y_{kmno} = \mu + Block_k + trtG_m + Week_n + Cow_{okm} + e_{kmno}$$

in which μ is the overall mean, $Block_k$ is the effect of the k^{th} block (1, 2, 3, 4, and 5), $trtG_m$ is the effect of the m^{th} treatment group (Non-Exercise and Exercise), $Week_n$ is the effect of the n^{th} week (1, 2, 3, 4, and 5), Cow_{okm} is the random effect of the o^{th} cow nested withing the k^{th} block and m^{th} treatment group ~ N(0, σ^2), and e_{kmno} is the random error ~ N(0, σ^2).

Claw lesion was treated as a binary variable and was analyzed using the following logistic, mixed-effect statistical model

$$Y_{kmnso} = Block_k + trtG_m + Time_n + trtG * Time_{mn} + claw_{sokm} + e_{kmnso}$$

where μ is the overall mean, $Block_k$ is the effect of the K^{th} block (1, 2, 3, 4, and 5), $trtG_m$ is the effect of the m^{th} treatment group (Non-Exercise and Exercise), $Time_n$ is the effect of the n^{th} day of data collection (Pre-trial and Follow-up), $trtG * Time_{mn}$ is the interaction effect between the m^{th} treatment group and the n^{th} data collection time, $claw(cow)_{sokm}$ is the random effect of the s^{th} claw nested within o^{th} cow, k^{th} block and m^{th} treatment group ~ N(0, σ^2), and e_{kmnso} is the random error ~ N(0, σ^2).

Data extracted for the original image analysis were analyzed using the following mixed-effect statistical model

$$\begin{aligned} Y_{jkmnqso} = {} & \mu + Block_j + Lpos_k + trtG_m + Week_n + AmbT_q + trtG * Week_{mn} \\ & + Limb(cow)_{sojm} + e_{jkmnqso} \end{aligned}$$

where μ is the overall mean, $Block_j$ is the effect of the J^{th} block (1, 2, 3, 4, and 5), $Lpos_k$ is the effect of K^{th} limb position (fore and hind), $trtG_m$ is the effect of the m^{th} treatment group (Non-Exercise and Exercise), $Week_n$ is the effect of the n^{th} week (week 1 and week 5), $AmbT_q$ is the effect of ambient temperature, $trtG * Week_{mn}$ is the interaction effect between the m^{th} treatment group and the n^{th} week, $Limb(cow)_{sojm}$ is the random effect of the s^{th} limb nested within o^{th} cow, k^{th} block and m^{th} treatment group ~ N(0, σ^2), and $e_{jkmnqso}$ is the random error ~ N(0, σ^2).

Also, normalized image analysis data were analyzed using the following mixed-effect statistical model

$$Y_{jkmnso} = \mu + Block_j + Lpos_k + trtG_m + Week_n + trtG * Week_{mn} + Limb(cow)_{sojm} + e_{jkmnso}$$

where μ is the overall mean, $Block_j$ is the effect of the J^{th} block (1, 2, 3, 4, and 5), $Lpos_k$ is the effect of K^{th} limb position (fore and hind), $trtG_m$ is the effect of the m^{th} treatment group (Non-Exercise and Exercise), $Week_n$ is the effect of the n^{th} week (week 1 and week 5), $trtG * Week_{mn}$ is the interaction effect between the m^{th} treatment group and the n^{th} week, $Limb(cow)_{sojm}$ is the random effect of the s^{th} limb nested within o^{th} cow, k^{th} block and m^{th} treatment group ~ N(0, σ^2), and e_{jkmnso} is the random error ~ N(0, σ^2).

For gait scoring, overall NRS score and the other six gait attributes including swinging out, arch back, tracking up, joint flexion, asymmetric step, and reluctance to bear weight were analyzed using the following mixed-effect statistical model

$$Y_{kmno} = \mu + Block_k + trtG_m + dPeriod_n + trtG * dPeriod_{mn} + Cow_{okm} + e_{kmno}$$

in which μ is the overall mean, $Block_k$ is the effect of the k^{th} block (1, 2, 3, 4, and 5), $trtG_m$ is the effect of the m^{th} treatment group (Non-Exercise and Exercise), $dPeriod_n$ is the effect of the n^{th} difference between periods (Post-trial – Pre-trial and Follow-up – Pre-trial), $trtG * dPeriod_{mn}$ is the interaction effect between the m^{th} treatment group and the n^{th} difference between periods, $Cow_{okm}$is the random effect of the o^{th} cow nested withing the k^{th} block and m^{th} treatment group ~ N(0, σ^2), and e_{kmno} is the random error ~ N(0, σ^2).

Residual analysis was conducted for all models to evaluate the assumptions that the within-group errors were homoscedastic, independent, and followed a normal distribution and to determine that the random effects were normally distributed and independent. This was done graphically following the procedures described by Pinheiro and Bates (2000). Variance models and serial correlation structures were used when the residual analysis indicated evidence that the assumptions were violated. Heteroscedasticity was modeled by using a variance model with different variances for each level of a stratification variable. Cow, group, week, and day were evaluated as stratification variables and the Akaike Information Criteria (AIC) was used as the criteria to select the model which best fit the data. Serial correlation structures were also evaluated to model the possible dependency among observations since the data contained repeated measures collected in different days (1 to 32 days). General, autoregressive of order 1, and compound symmetry were the correlation structures evaluated. For stratification variables, the AIC was also used to select the one the best adjusted to the data. The F-test was used to evaluate the statistical significance of the fixed effects in the models adopting a significance level $\alpha < 0.05$. Estimated effects were evaluated using marginal means with Bonferroni P-value adjustment for multiple comparison of means.

3.4. RESULTS AND DISCUSSION

3.4.1. Step Activity

No statistically significant difference was found in step activity between treatment groups over the time of the trial. However, Exercise cows tended to express a higher number of steps than Non-Exercise cows (705 ± 71.4 vs 518 ± 67.9 steps/d, respectively, denominator degrees of freedom (ddf) = 24, F-value = 3.59, P = 0.07). We hypothesized that Exercise cows would show higher step activity after access to outdoor than Non-exercise cows, as a result of more freedom of movement that was provided, but the higher number of steps taken by Exercise cows compared to Non-exercise cows were not statistically significant. In fact, both Exercise and Non-Exercise cows expressed lower overall step activity than dry cows from the same herd housed in tie-stalls (no exercise access) reported in a previous study (Shepley & Vasseur, 2021b). However, as step activity was numerically around 1.4-fold greater for Exercise cows, it is possible that, when offered housing outdoor access that provided greater opportunity of movement, these cows did express greater locomotor activity. It is also possible that a number of factors may have influenced the level of locomotor activity, such as space allowance outdoors, frequency of outdoor access provision, and duration of periods of access, which warrants further exploration to improve management options for outdoor access provision in tie-stall herds.

It is important to note that individual variability, regardless of housing system, may contribute to total locomotor activity performed by a cow. Indeed, in the current study, variability in step activity between cows remains high in Non-Exercise cows during the trial, while the variability in step activity has narrowed over time for Exercise cows (Figure 3.4.1). It is consistent with Shepley, Lensink, Leruste, et al. (2020) who found no significant differences between step activity in the straw yard and free stall housing after free access to pasture, but reported a positive correlation between step activity – independent of housing system – and visits to pasture. The authors of that study suggested that cows opting to visit the pasture area more often were the animals that had a greater need to express locomotor activity and would likely have higher step activity as a result regardless of the housing system they were provided. High variability in our Non-Exercise cows may reflect a greater number of individual cows in this treatment group that had higher locomotor needs by comparison to Exercise cows, contributing to the lack of significant differences through the inflation of steps by these individuals. These findings advocate for taking into account individual needs as well as the group-level view in future research investigating outdoor access in dairy cows.

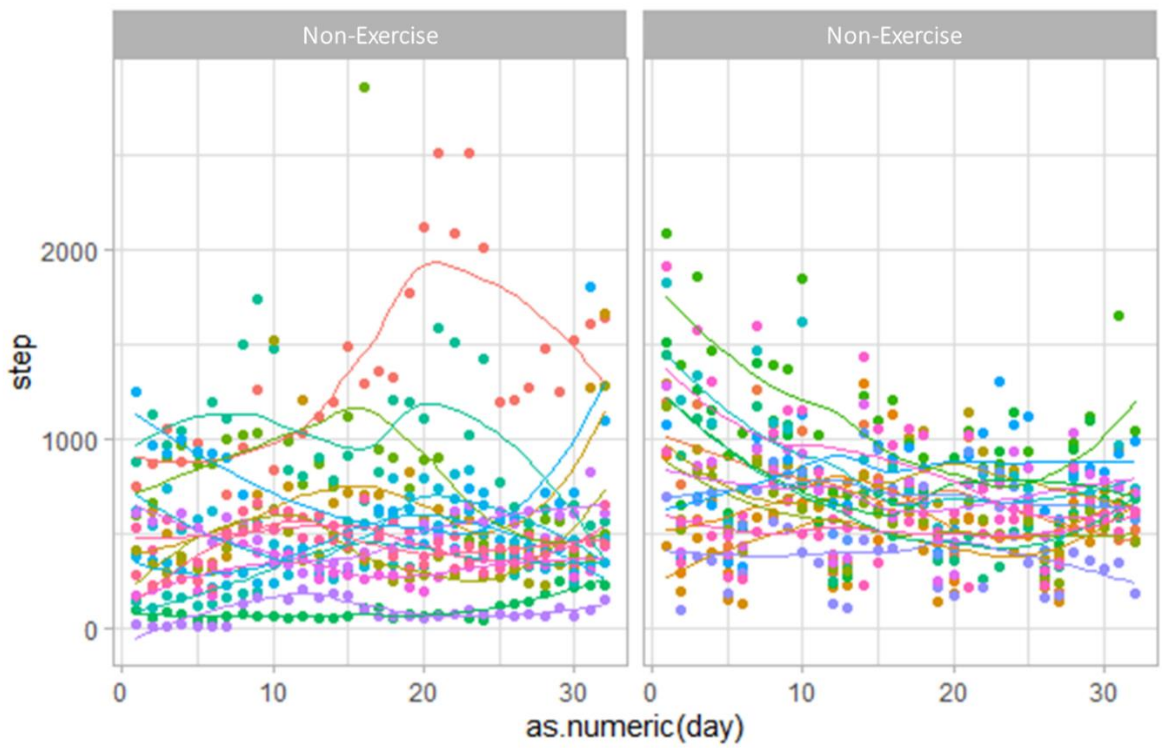

Figure 3.4.1. Number of steps/d taken by Non-Exercise (left) and Exercise (right) cows during the 5 weeks (35 days) of the trial. Each color represents an individual cow.

3.4.2. Gait Scoring

No statistically significant effects were found between treatment groups and periods for the changes in the overall gait score and the six gait attributes (Supplementary Table 3.7.1). The average NRS score of Exercise cows numerically decreased from 2.8 at Pre-trial to 1.8 and 1.7 at Post-trial and Follow-up, respectively, while the average NRS score of Non-Exercise cows changed from 2.9 at Pre-trial to 2.8 and 2.5 at Post-trial and Follow-up, respectively (Figure 3.4.2). The same numerically decrease occurred for 3 main gait attributes – tracking-up, asymmetric steps, and reluctance to bear weight (Supplementary Figure 3.7.2). No severely lame cows (NRS ≥ 4) were enrolled in our study at the beginning and no cows became severely lame across the study. Regarding lameness prevalence, at Pre-trial a total of 8 cows (5 Exercise and 3 Non-Exercise cows) were scored as moderately lame (NRS = 3 or 3.5). At Post-trial and Follow-up, 4 and 2 Non-Exercise cows were scored as moderately lame, respectively, while no Exercise cows were scored as moderately lame.

The results corroborate Shepley and Vasseur (2021b), who found numerical decreases in NRS score and the other six gait attributes after releasing tie-stall housed cows into a deep-bedded loose-housing system for 8 weeks of dry-off period. This decrease was not significant for the NRS score and the other gait attributes except joint flexion (Shepley & Vasseur, 2021b). Gait score did not differ when access to pasture was provided only nighttime hours for free-stall cows over a period of 12 weeks (Chapinal, Goldhawk, et al., 2010). However, improvement in gait was found in other studies that provided pasture access to cows who were otherwise housed in indoor housing systems (e.g., free-stall, Chapinal et al. (2013); Hernandez-Mendo et al. (2007); cubicle design, (Olmos et al., 2009). A key difference between the studies reporting significant versus non-significant gait improvement related to outdoor access, including the results of our current study, may be the amount of time that access to outdoor space was provided and or the frequency of access, both of which can affect the effectiveness of outdoor access (Shepley & Vasseur, 2021a). The lack of significant difference in gait changes between our two treatments over the 5 weeks of application may also be due to the small sample of cows selected for gait analysis and the wide variation in individual cows' gait scores in both treatments at the beginning of the study.

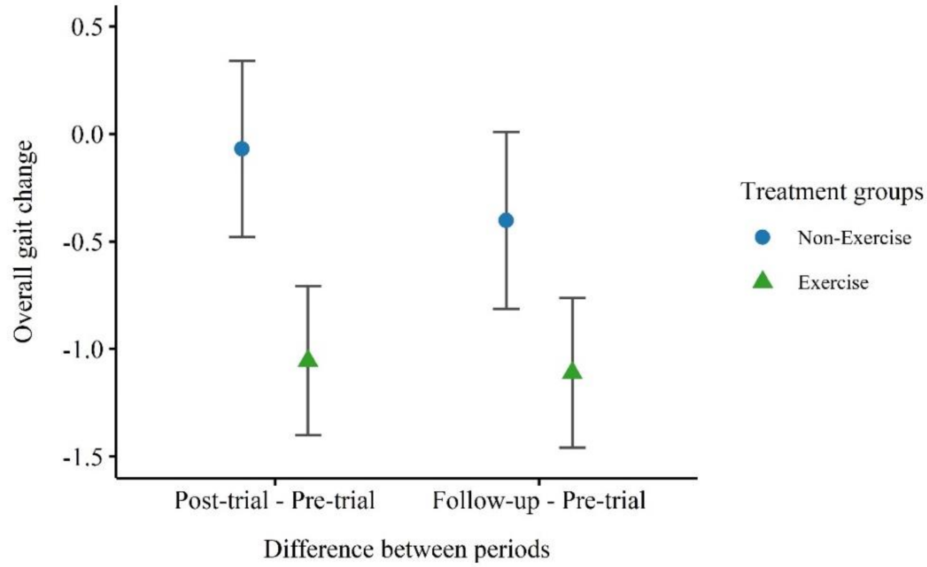

Figure 3.4.2. Change in overall gait (NRS) score between periods (Post-trial – Pre-trial and Follow-up – Pre-trial) for treatment groups (Non-Exercise and Exercise).

3.4.3. Claw Lesion Assessment

A total of 38 claw lesions were observed at the two data collection periods: Pre-trial, 21 claw lesions within 13 cows; Follow-up, 17 claw lesions within 11 cows. All of the observed lesions were sole hemorrhages (SH) and were located in zone 4 (37 claws) and zone 5 (1 claw). The severity scores of the lesions showed a distribution of 21 lesions with score 1 (55.3% of the lesions), 13 lesions with score 2 (34.2% of the lesions), 4 lesions with score 3 (10.5% of the lesions) and 0 lesion with score 4. The prevalence of claws with SH did not change for both Exercise (7.50% to 6.67%; $p = 0.58$) and Non-Exercise cows (10% to 8.04%; $P = 0.16$) from Pre-trial to Follow-up. The severity of claw lesions, also, did not yield an effect of periods or treatment groups ($P > 0.05$).

The only source of comparison to our results is an epidemiological study conducted in Canadian tie-stall dairies that reported a 25.7% cow-level prevalence of any claw lesions and 7.1% prevalence of SH (Cramer et al., 2008). There is no study that reported the claw-level prevalence of claw lesion in tie-stall barns which make it difficult to compare our results. In addition, SH is a less severe lesion by comparison to the other claw lesions typically reported (Nocek, 1997). Even within different severity scores of SH, the mild SH scores are generally underreported by hoof trimmers (Solano et al., 2016), therefore, it is possible that our methodology, which was designed to report less severe SH at the claw-level, may have led to a higher number of reported SH in our study (55.3%) compared to the above epidemiological study.

The absence of negative and positive effects of outdoor access application on claw lesions is in accordance with our hypothesis and it confirmed Loberg et al. (2004) study that found no significant effect of various levels of outdoor access on claw lesions in cows housed in tie-stall. Bielfeldt et al. (2005) also found no significant differences of claw sole disorders between cows housed in tie-stall barns with and without outdoor access to exercise. However, a full literature review on the effect of movement opportunity on cow health and comfort showed that pasture access has a positive effect on hoof health, particularly non-infectious claw disorders (Shepley & Vasseur, 2021a), possibly as the results of more comfortable footing on pasture and increased blood flow in the legs that improves hoof health. These discrepancies with the results of our current study might be because of the low prevalence of claw lesions and different levels of outdoor access application (i.e., 1hr/d in our study to seasonal or year-around access to pasture in other studies). More studies are required to be conducted to understand possible benefits of outdoor access on tie-stall cows and hoof health.

3.4.4. Hoof Thermography

Original image analysis: There are not statistically differences between treatment groups (Exercise and Non-Exercise) and time (week 1 vs week 5) for all thermal variables: CB-Max, CB-Mean, CB-Std and ΔT (Supplementary Table 3.7.2). All the thermal variables were statistically affected by ambient temperature ($P < 0.001$) which is consistent with previous studies (Alsaaod et al., 2015; Landgraf et al., 2014; Wilhelm et al., 2015).

Normalized image analysis: A statistically significant interaction was observed in one thermography feature i.e., kurtosis between treatment groups and weeks ($P < 0.0001$, Supplementary Table 3.7.2). Kurtosis value decreased for both Non-Exercise and Exercise groups from week 1 to week 5. Within each week, treatment groups were only statistically different on week 1 (Figure 3.4.3). It means that Exercise cows started the trial with a higher kurtosis value than Non-Exercise cows at week 1 (reason unknown). Although the reduction in kurtosis between week 1 and 5 was higher in Exercise cows (from 2.61 ± 0.04 to 2.44 ± 0.04)

than in Non-Exercise cows (from 2.44 ± 0.04 to 2.35 ± 0.04), there are uncertainties in the effect of exercise on the kurtosis values. Indeed, kurtosis as sole metric may not be sufficient to interpret the results further.

One of the possible risk factors of providing outdoor access on cow's hoof health could be the impact of walking on hard, rough, frozen, and uneven surfaces that could lead to mechanically induced laminitis (Shearer et al., 2015) which can be identified by hoof surface thermography even at early stages (Gianesella et al., 2018; Nikkhah et al., 2005; Wood et al., 2015). We hypothesized that outdoor access would not compromise cow's hoof health and increase hoof surface temperature as a result of inflammation associated with laminitis. The results of both thermography analytical approaches showed that hoof surface temperature is probably not influenced by application of 1hr/d outdoor access, which is consistent with our hypothesis.

Because the normalized image analysis showed a lower kurtosis value at week 5 by comparison to week 1 of the trial, there is a possibility of improvement in temperature distribution throughout the coronary band and the skin control area (Figure 3.3.7, B) after a period of daily outdoor access. It might be as a result of increased blood circulation in the feet area that supplies oxygen and nutrients to claw tissue and remove inflammatory processes toxins that could prevent the development of laminitis (Bergsten, 2003; Boosman et al., 1991) and regulate hoof surface temperature. To our knowledge this study is the first study to look at the effect of outdoor access on cow's foot thermography. More investigations are needed to confirm that if daily outdoor access or any other kinds of exercise could have a positive effect on regulating foot surface temperature and its association with overall hoof health.

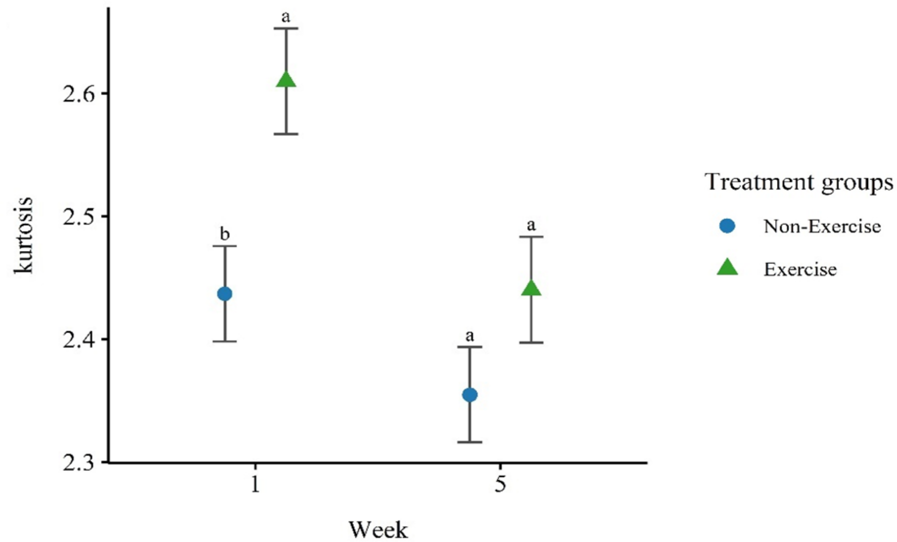

Figure 3.4.3. Kurtosis values obtained from normalized image analysis of treatment groups (Non-Exercise and Exercise) at Week 1 and Week 5. Different letters (a and b) on top of box plots indicate significant difference (P<0.05).

3.5. CONCLUSION

The present study sought to determine whether locomotor activity (number of steps), gait score (overall NRS score and 6 gait attributes), and hoof health (claw lesion and hoof surface temperature) differed after the provision of a 5-week period of daily outdoor exercise to tie-stall-housed dairy cows. Although locomotor activity increased overtime and the overall gait score and 3 key gait attributes improved numerically, the changes were not significant. The changes in level of activity may be impacted by individual variability of cows to utilize differently the increased movement opportunity provided during the study, while our gait results may be due to the small sample size and wide variation in gait scores at the beginning of the study. In addition, further work is needed to determine what level of outdoor access in terms of duration and frequency of access is required to be effective in increasing cows' locomotor activity and improve gait score. Daily outdoor exercise had little impact on hoof health conditions. Indeed, no significant changes in clinical assessment of hoof lesions nor in the hoof thermography, which was intended to detect temperature rise caused by laminitis, were found. This suggests that daily outdoor access can be provided to lactating tie-stall cows without adversely affecting the hoof health, but that further research is needed to determine if providing different types or level of outdoor access can be used to benefit hoof and leg health.

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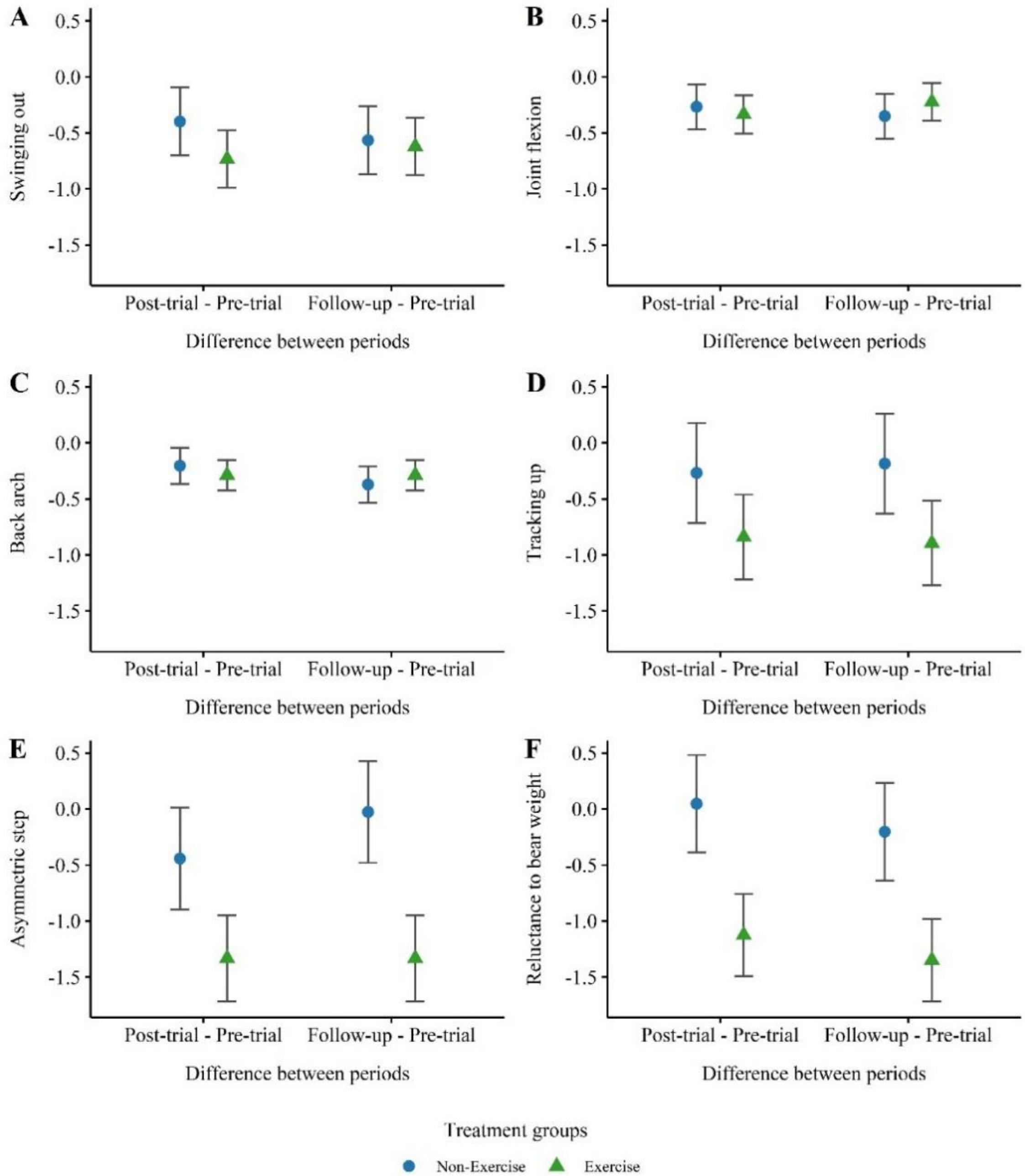
3.7. SUPPLEMENTARY MATERIAL

```
clc; close all; clear all;

% FontSize=10;FontSize_xlabel=9;FontSize_ylabel=9;
%% Initiation inputs
Original = imread('image.jpg');
Original = rgb2gray(Original);
imtool(Original)
%% Cropped images
image = imread('image.png');
F_image = FE(image,"image");

%%
Result = [F_image]
writetable(Result,'R1.xlsx','Sheet',1);

% image = rgb2gray(Original);
% image = double(image);
% image = Normalize(image);
% imtool(image)
%% functions
function [F]= FE(im,FVarNames)
im = double(im);
im = Normalize(im);
F = [mean(im(:))
     std(im(:))
     skewness(im(:))
     kurtosis(im(:))
     rms(im(:))];

F = array2table(F);
F.Properties.VariableNames = FVarNames;
F.Properties.RowNames = ["Mean","Std","Skewness","Kurtosis","RMS"];
end
function XN = Normalize(X,beta)
if nargin<2
    beta=1;
end
Xmin=min(X(:));
Xmax=max(X(:));
XN=((X-Xmin)/(Xmax-Xmin)).^beta;
end
```

Supplementary Figure 3.7.1. Matlab script used for Normalized thermal image analysis consists of segmenting the square area, i.e., the coronary band and skin control area, and extracting statistic features.

Supplementary Table 3.7.1. Change in gait score between periods (P), i.e., Post-trial – Pre-trial and Follow-up – Pre-trial for treatment groups (T), i.e., Non-Exercise and Exercise.

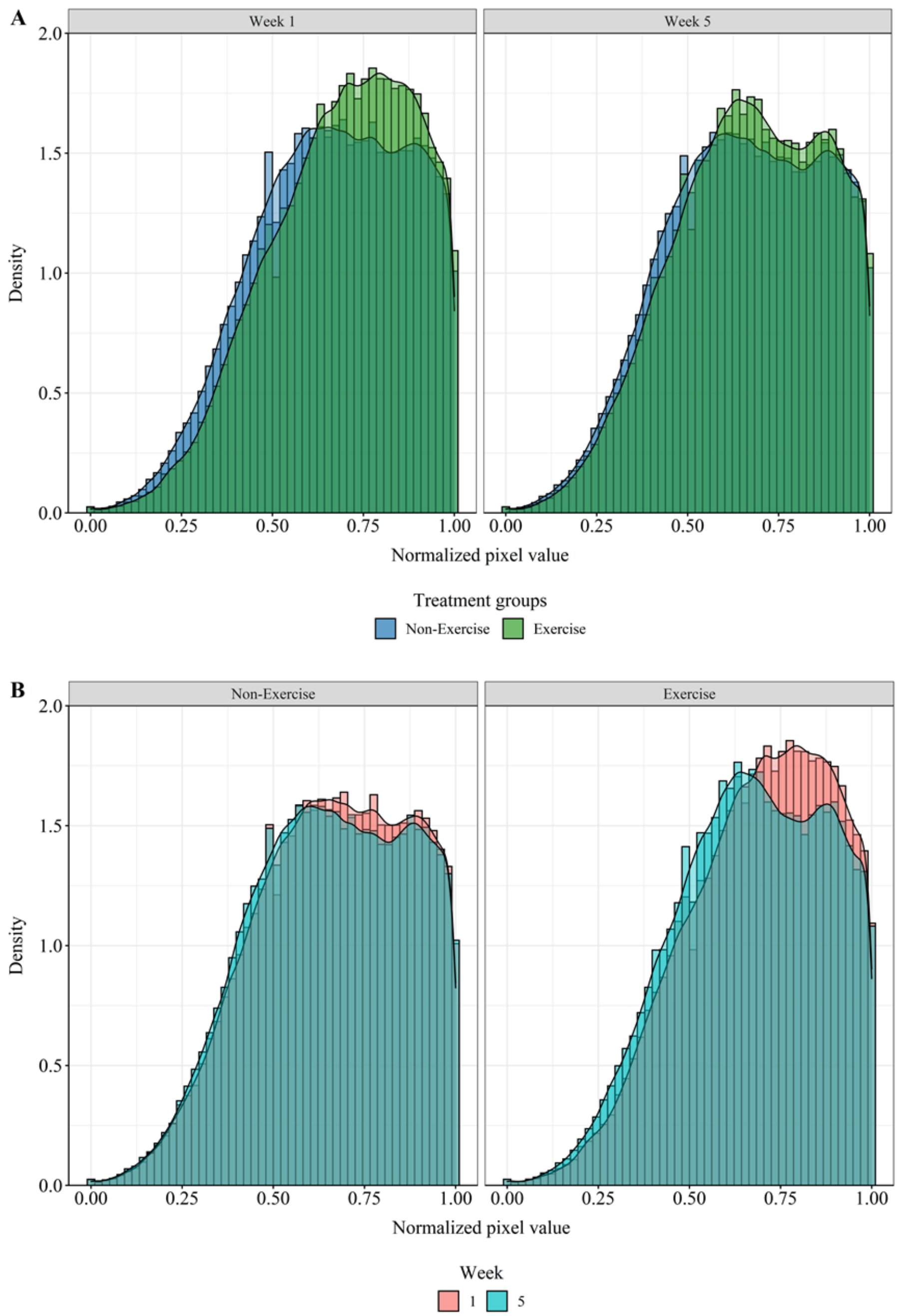
Variable	**Treatment Group**		**Difference between periods**		**Significance**		
	Non-Exercise	Exercise	Pre-trial – Post-trial	Follow-up – Pre-trial	T	P	T×P
NRS	0.23 ± 0.4	-1.08 ± 0.34	-0.56 ± 0.22	-0.76 ± 0.27	0.14	0.09	0.21
Swing	-0.48 ± 0.29	-0.68 ± 0.24	-0.57 ± 0.2	-0.59 ± 0.2	0.61	0.82	0.27
Joint Flexion	-0.31 ± 0.18	-0.28 ± 0.16	-0.30 ± 0.13	-0.29 ± 0.13	0.90	.90	0.37
Back Arch	-0.29 ± 0.15	-0.29 ± 0.13	-0.25 ± 0.11	-0.33 ± 0.11	1.0	0.23	0.23
Tracking-Up	-0.23 ± 0.43	-0.87 ± 0.37	-0.55 ± 0.29	-0.54 ± 0.29	0.28	0.93	0.66
Asymmetry	-0.23 ± 0.43	-1.33 ± 0.36	-0.89 ± 0.3	-0.68 ± 0.3	0.08	0.31	0.31
Weight-Bearing	-0.08 ± 0.41	-1.24 ± 0.35	-0.54 ± 0.29	-0.78 ± 0.29	0.06	0.24	0.94



Supplementary Figure 3.7.2. Change in six gait attributes score (A, swinging out; B, joint flexion; C, back arch; D, tracking up; E, asymmetry step; F, reluctant to bear weight) between periods (P), i.e., Post-trial – Pre-trial and Follow-up – Pre-trial for treatment groups (T), i.e., Non-Exercise and Exercise.

Supplementary Table 3.7.2. Thermal variables obtained from original image analysis, presented as ℃, and, statistical parameters obtained from normalized image analysis, presented as normalized pixel values for cows in different treatment groups (T) at week (W) 1 and 5.

Thermal Variable	**Treatment Group**		**Week**		**Significance**		
	Non-Exercise	Exercise	Week 1	Week 5	T	W	T×W
Original Image analysis							
CB-Max	34.8 ± 0.1	34.2 ± 0.13	34.6 ± 0.11	34.4 ± 0.1	0.0004	0.06	0.63
CB-Mean	29.9 ± 0.09	29.4 ± 0.1	29.9 ± 0.09	29.4 ± 0.08	<0.0001	<0.0001	0.16
CB-Std	2.33 ± 0.04	2.06 ± 0.04	2.18 ± 0.03	2.22 ± 0.03	<0.0001	0.35	0.33
ΔT	7.2 ± 0.18	6.23 ± 0.18	6.5 ± 0.16	6.93 ± 0.14	0.0003	0.01	0.36
Image Normalization							
Mean	0.66 ± 0.006	0.68 ± 0.006	0.68 ± 0.005	0.66 ± 0.005	0.03	0.03	0.22
Std	0.19 ± 0.003	0.18 ± 0.003	0.18 ± 0.002	0.19 ± 0.002	0.008	0.1	0.27
Skewness	-0.19 ± 0.03	-0.31 ± 0.03	-0.29 ± 0.026	-0.21 ± 0.026	0.006	0.02	0.11
Kurtosis	2.4 ± 0.04	2.53 ± 0.04	2.52 ± 0.03	2.4 ± 0.02	0.24	<0.0001	<0.0001



Supplementary Figure 3.7.3. Histogram of normalized pixel values of all thermal images captured from treatment groups at week 1 and week 5. X axis shows the normalized pixel values ranging from 0 (represents the lowest temperature) to 1 (represents the highest temperature). Y axis shows frequency of the pixels. Graph A and B are showing the same histograms overlying each other based on the treatment groups (A) and weeks (B).

CHAPTER 4 – GENERAL DISCUSSION

This thesis covered two parts: 1) a systematic scoping review of technology applications in bovine gait analysis following PRISMA guidelines, and 2) an experimental study evaluating the effect of outdoor access on gait and hoof health of tie-stall-housed dairy cows.

Our literature review chapter explored the different technological approaches that have been applied to bovine gait analysis and discussed their usefulness in assessing cow gait. Considering the limitations of subjective gait analysis methods, quantitative methods using technologies can be an advantageous and reliable alternative for gait analysis purposes. The objective of the scoping review presented in Chapter 2 was to perform a review of the current literature to map research trends as well as explore the wide range of gait analysis technologies and the purposes for which they have been employed. The first point to acknowledge is that quantitative gait analysis in cows was considerably less covered when compared to a similar review in equine with the same scope. Secondly, lameness detection was the primary research aim for studies utilizing gait technologies, with less focus on the mechanisms behind cow gait, independent of lameness. It was an expected result due to the sole role of the cow as a livestock animal (vs. equine being also used as a sport and leisure animal) and the importance of lameness as a major welfare and health problem in the dairy industry. The scoping review also highlighted the gaps in the use of technology regarding the evaluation of on-farm management and environmental factors associated with cow's welfare (e.g., housing systems, outdoor access, etc.), the investigation of cow gait biomechanics in early life, and the comparison between different breeds and size of cows. We also found a gap in the use of gait technologies in the beef cattle industry. Reviewing the gait analysis technologies resulted in three major categories: Force and Pressure platforms, Vision-based technologies, and Accelerometers. The most popular gait technologies were Force and Pressure platforms followed by Vision-based technologies, while Accelerometers stood as the most frequently used technologies when looking at studies from the last five years.

The research presented in Chapter 3 studied tie-stall housed lactating Holstein cows that were enrolled in an experiment aiming to evaluate the effect of 1hr daily outdoor access on cow gait and hoof health. We recorded step activity of cows via pedometers, finding a tendency for Exercise cows to exhibit greater step activity when compared with Non-Exercise cows. Similarly, while gait analysis results obtained through a visual gait scoring, i.e., NRS, showed greater numeric improvement in the gait of Exercise cows than reported in Non-Exercise cows, the differences between treatment groups were not statistically significant. These results reiterate a need to find a suitable combination of frequency and duration of outdoor access in future studies that will result in greater differences in gait improvement, but that outdoor access shows promise for maintaining and or improving gait of tie-stall dairy cows.

The results of hoof health evaluation (i.e., claw lesion assessment and hoof surface thermography) showed little impact of outdoor access on hoof pathologies development; neither the number and severity of sole hemorrhages (the only claw lesion seen in this study) nor the hoof surface temperatures differed between treatment groups or over time. These results suggest that daily outdoor access can be provided to tie-stall cows without adversely affecting hoof health. Further research is needed to determine if providing different types or levels of outdoor access can be used to benefit hoof and leg health.

Overall, understanding the impact of outdoor access on welfare and lameness of long-term confined cows in tie-stall farms, particularly on gait and hoof health, can help address the major challenges facing dairy cattle. It is an essential step for providing producers with knowledge of sufficient and effective forms of outdoor access to enhance cow condition. Furthermore, understanding the existing technological options for a more objective understanding of cow gait can provide an additional piece of the puzzle in the effort to address lameness in the dairy industry. Future research combining objective, technology-based analysis of gait, with clinical measures of hoof and leg health in studies investigating outdoor access in dairy cattle can provide more precise insight on how this provision of outdoor access is impacting the cow.

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