GAIT ASSESSMENT OF DAIRY CATTLE

by

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Abstract

Hoof and leg pathologies are important to the welfare of dairy cows and the profitability of farms; however, to date researchers have had little success in detecting cows with hoof pathologies using current gait analysis methods which are poorly defined and un-validated. The first aim of my thesis was to describe the walking gait profile of cows with no visible hoof pathologies, compare this with profiles of cows with sole haemorrhages, and cows with sole ulcers, and determine which gait measures were valid and reliable indicators of hoof pathologies. The second aim of my thesis was to examine how udder size and flooring surface influenced the way cows walk, and how these effects varied for cows with different hoof pathologies. Analyses of cow gait, using kinematic techniques and subjective gait assessment, showed distinct differences among cows with no visible hoof pathologies compared to those with painful sole ulcers. Cows with sole ulcers probably walked differently to reduce loading on the affected leg. The gait pattern of cows before and after milking was also different; cows had longer strides and walked more quickly after milking. These results suggest that the most suitable time to conduct on-farm assessments of dairy cattle gait is after milking. Rubber flooring improved the gait of both cows with and without sole ulcers. Lame cattle showed the greatest improvement, suggesting that rubber flooring provided a more secure and comfortable surface for cows to walk on. This research provides novel contributions to the field of dairy cattle lameness; this research was the first study to quantify and validate the gait of cows with and without hoof pathologies using computer-aided kinematic techniques and was also the first to explicitly define, validate, and test the reliability of an overall gait score and individual behavioural gait attributes. Although there is still much work to be done to better understand how hoof and leg pathologies affect cows, the research described here provides insight into how dairy cows with and without hoof pathologies walk and how certain variables such as milking and flooring influence cow walking patterns.

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List of Abbreviations

BCS	Body condition score
BM	Body mass
DIM	Days in milk
H	Healthy
HO	Hoof-off
HS	Hoof strike
LF	Left front hoof
LR	Left rear hoof
NRS	Numerical rating system
nSU	No sole ulcer
RF	Right front hoof
RR	Right rear hoof
SD	Standard deviation
SEM	Standard error of the mean
SH	Sole haemorrhage
SU	Sole ulcer
TMR	Total mixed ration
VAS	Visual analogue scale

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Ab imo pectore.

Co-Authorship Statement

Chapter 2:
I was responsible for the experimental design, data collection, all statistical analyses, and writing the manuscript.
David Sanderson and Dan Weary contributed to the experimental design, the choice of statistical tests and to the interpretation and presentation of the manuscript.

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Dan Weary contributed to the experimental design, the choice of statistical tests and to the interpretation and presentation of the manuscript.

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CHAPTER 1: General Introduction

The veterinarian and popular writer James Herriot described being summoned by a farmer who thought one of his cows was lame because "she's on three legs". When Herriot went to examine the cow she was indeed extremely lame, and when approached she moved by hopping and only occasionally touched the injured leg on the ground. After lifting her hoof Herriot discovered that the problem was a metal stud buried in her hoof and quickly removed it (Herriot, 1982). In contrast, veterinarian David Morrow presented a case of a dairy cow that became lame after calving. Five days after moving into the milking herd she was not eating, had dropped in milk production, and had difficulty standing up and lying down. When she stood, she lowered her head, arched her back, and shifted her weight back and forth between her front feet. When forced to move she had a short and stiff walk. Morrow found severe haemorrhages on the soles of her hooves and prescribed "bed rest" for the cow (Morrow, 1966).

These 2 examples demonstrate that abnormal behaviour is widely used to identify lameness in cattle, although different people have different criteria for what constitutes lameness. The first case used weight-bearing on 3 legs as a definition of lameness, whereas the second case used difficulty in rising, abnormal posture, and shifting weight between the legs. This leads us to ask which behaviours are the best indicators of lameness and are there any factors that might influence them. Indeed, since people have different ideas of what lameness is, how should we define it?

1.1 What is lameness?

Over the last 25 years much work has been published about lameness in dairy cattle, yet the concept of lameness has not been discussed in the literature. The dictionary definition of lame, with reference to a person or animal, has been defined as "crippled through injury to or defect in, a limb; specifically, disabled in the foot or leg, so as to walk haltingly or be unable to walk", and lameness has been defined as "the condition or quality of being lame" (OED, 1989).

Several problems arise in trying to understand the concept of lameness in the scientific literature. The first problem is the different ways the term has been used. In some cases, lameness has been used to refer to a pathological condition of the hooves and legs. For example, lameness has been defined using terms such as "leg problem" (Sanotra et al., 2001) and "leg weakness" (Kestin et al., 1992), although these descriptions are so general that if researchers were classifying animals as lame or healthy based only on these descriptions, animals may be categorized inconsistently. In other cases, researchers have defined lameness as a movement disorder. For example, Clements et al. (2002) defined lameness as a "locomotor disorder" and Webster (1993) referred to lameness as "a disability in the movement of limbs", but again these descriptions are broad and there is no research specifically describing normal movement of cows versus movement disorders. Definitions used in research need to be detailed enough to allow other researchers to record lameness in the same way (Martin and Bateson, 1998), yet the terms and descriptions discussed so far do not provide this level of specificity. In fact, some descriptions would probably cover many animals that would not be included by more specific definitions.

Some researchers have created definitions that attempt to include both the cause of lameness (pathological states) and the effect (abnormal gait). For example, Greenough (1991) provided a more explicit definition of lameness as "a clinical sign or symptom of a disorder that causes a disturbance in locomotion. This disturbance is observed as an aberration of gait that may be caused by metabolic or systemic disturbance, injury to the musculo-skeletal system, or infection." Although Greenough (1991) is clear about the causes of lameness, he is less specific in describing the effects. The use of "aberration of gait" and "disturbance" implies that lameness is a deviation from normal gait, but both these descriptions are open to interpretation.

The wide range of definitions of lameness, and the ambiguous nature of these descriptions, may explain some of the large variation in the reported incidence of lameness in dairy cattle. For example, estimates range from 12 - 70% (Winckler and Willen, 2001a; Green et al., 2002).

A second problem involves the idea that lameness can be quantified along a single dimension. A common approach to measuring lameness is to use a one-dimensional scale with varying degrees of severity ranging from “not lame” to “severely lame” (see Figure 1.1a). However, lameness, by all the definitions given above, can involve a wide range of causes including sole ulcers, white line separation, and interdigital hyperplasia, and there is no reason to believe that these different conditions will create outcomes that differ only in degree. Therefore, we may need a classificatory approach that identifies specific hoof and leg pathologies and the consequent effects on animal gait (see Figure 1.1b). When we take this approach, we might see the word lameness more like the word illness. When a person says that they are ill, a quantitative expression of “very ill” versus “slightly ill” is of interest, but effective treatment will require that the specific causes and symptoms of the illness be determined. In a similar way, lameness researchers might better identify causes and specific signs, rather than simply estimate overall severity.

Given how differently the term has been used, lameness is best treated as an “umbrella” term referring generally to gait deviations as a result of hoof or leg disease, injury or infection. However, this type of term is not very useful for scientific purposes. Instead, I suggest that researchers actually need to study each of the distinct hoof and leg pathologies and the deviations in gait that they bring about.

In conclusion, progress in understanding how hoof and leg injuries and disease affect animals will require moving beyond grouping different phenomenon together under an umbrella term such as “lameness” and instead systematically investigate the effects of hoof and leg injuries and diseases. In the studies reviewed in this chapter, I will specify the actual variables measured, rather than using the general term “lameness” wherever possible. In cases where I use the word “lame” I am referring to any detectable deviations of gait arising from disease, injury or infection of the hooves and legs.

1.2 The importance of studying hoof and leg pathologies

In recent years cows with hoof and leg pathologies have become a focus for those concerned with both the welfare and productivity of farm animals. Agricultural agencies and welfare bodies such as the UK Department for Environment, Food and Rural Affairs (DEFRA, 2004), and the UK Farm Animal Welfare Council (FAWC, 1997), recognize that hoof and leg injuries and disease are a research priority primarily because: a) they compromise a cow's welfare; b) the large number of animals involved; and c) the monetary losses they cause to producers.

A recent survey of US animal science faculty members found that over 80% of respondents were concerned by the levels of lameness in dairy cattle (Heleski et al., 2004). Approximately 1.1 million, 2.2 million, and 9.0 million cows are producing milk on dairy farms today in Canada, the UK and the USA, respectively (CDIC, 2005a; MDC, 2005; USDA, 2005). Various studies have estimated the percentage of cows affected by lameness (i.e., gait deviations resulting from hoof and leg pathologies) (see Table 1.1) and show that a large number of cows have hoof lesions. Hoof and leg injuries and disease are not new problems, although incidences reported in the past have been lower. For example, a 1977 survey reported 6 new hoof injury cases per 100 cows per year (Russell et al., 1982). In comparison, Hedges et al. (2001) reported an incidence of 69 new cases per 100 cows per year. Recent research suggested that the rise in hoof and leg pathologies was linked to the demand for greater productivity in dairy cattle over the last few decades (Koenig et al., 2005; Oltenacu and Algers, 2005). Indeed, the average daily milk production of Holstein dairy cows in the USA has more than doubled in the last 40 years from 13 kg per cow per day in 1965 to 28 kg per cow per day in 2003 (CDIC, 2005b). To achieve greater productivity many producers have: a) improved management on farms (e.g., controlled environments where temperature, ventilation and lighting are regulated through indoor housing and cows are closely monitored); and b) concentrated on selective breeding for high milk yield (Oltenacu and Algers, 2005). However, studies on dairy cattle report that confined, artificial environments cause development of sole lesions (Greenough and Vermunt, 1991; Bergsten and Frank, 1996) and Rauw et al. (1998) described that because so many resources are channelled into selection for high milk yield, cows are left unable to respond to other demands, such as immune responses to hoof and leg diseases.

As the incidence of hoof and leg injuries and disease in dairy cows has grown, so too has the concern by animal welfare advocates for those animals that are affected and at risk. For example, the FAWC (1997) recognized that lameness is unacceptably high in dairy cattle. Animal welfare is concerned with the quality of life of an animal and currently 3 areas of focus exist in this field: biological functioning (e.g., is the cow healthy?); subjective states (e.g., does the cow experience pain?); and natural living (e.g., is the cow able to perform its natural repertoire of behaviours?) (Fraser et al., 1997). Hoof and leg injuries and disease can negatively affect all 3 areas.

Firstly, the biological functioning of cows with hoof and leg pathologies is, by definition, compromised. Apart from the immediate detriment to health from the injury or disease, there are also other health effects. Cattle with hoof disorders, for example, experience longer calving to conception intervals (Hernandez et al., 2005), reduced milk production (Juarez et al., 2003), and increased susceptibility to other diseases (Enting et al., 1997). Secondly, although the assessment of whether an animal is experiencing pain as a result of hoof injuries or disease is difficult, there is some evidence to suggest that cows with leg injuries or disease are in pain. For example, giving cows an analgesic improves gait of lame cows (high gait scores) but not for healthy cows (low gait scores) (Rushen et al., 2006). Thirdly, the ability of cows with hoof or leg pathologies to engage in natural behaviours can be compromised. For example, Juarez et al. (2003) showed that lame cows (high gait scores) spent more time lying down than non-lame cows (59 vs. 46%, respectively) and consequently, these cows have less time to feed (O'Callaghan, 2002).

Another animal welfare concern is the length of time before hoof and leg injuries and disease are actually detected. This may vary depending on the type of injury or disease, and the detection methods. Currently, methods that evaluate gait have been inadequate at detecting cattle with hoof pathologies and many cases go on for months before identification and treatment. For example, Whay et al. (2003) reported that producers identified only 1 of every 4 cases of dairy cattle with hoof injuries or disease, and in another study 13 of 15 producers stated that they could only identify cows that showed an obvious limp (Mill and Ward, 1994). This poor performance suggests that current detection methods are not effective and more refined methods of gait analysis are needed for early detection of hoof pathologies.

In addition to the impact on animal welfare, producers experience considerable monetary loss from hoof and leg pathologies. Bennett et al. (1999) estimated that the UK dairy industry loses approximately £39 - 121 million due to costs associated with lameness. These costs can be categorized as direct (costs of treatment, prevention, and losses in expected output) and indirect (increased risk of associated health problems and premature culling). Direct costs can be relatively straightforward to calculate, for example, the cost of treating an injury, such as a sole ulcer, in the UK is approximately £15 (Kossaibati and Esslemont, 1997). Other researchers have investigated the effect of hoof and leg injuries and disease specifically on milk production and report an estimated milk loss of 360 kg per cow per year in the UK (Green et al., 2002) and a 295 kg decrease per cow per year in the US (Warnick et al., 2001). These losses are modest in relation to the average annual milk production per cow (9658 kg in Canada; CDIC, 2005b) but still represent $190 in lost milk per injured cow in Canada. The variation in loss may be due in part to differences in how the data were analyzed or which pathologies were included in each study. Nonetheless, given the cost in lost milk per animal alone and the high incidence of animals with hoof and leg pathologies, the overall costs associated with these pathologies are high.

Indirect costs tend to be harder to quantify. For example, collecting information on the effects of hoof and leg pathologies on herd fertility is complicated by the many factors contributing to fertility, such as calving intervals, services per conception, and risk of associated health problems. Nonetheless, Kossaibati and Esslemont (1997) included herd fertility in their model and calculated the average cost of hoof and leg pathologies per cow (direct and indirect) in the UK as £273. Although studies report variation in the amount of monetary losses, it is clear that hoof and leg injuries and disease are costly to producers.

To summarize, hoof and leg pathologies are important for 2 reasons. Firstly, they compromise animal welfare and secondly, they result in substantial monetary losses for the producer.

1.3 Measuring hoof and leg pathologies

Hoof and leg pathologies cover a wide range of diseases and injuries including haemorrhages on the sole, infections of the digits such as digital and interdigital dermatitis, and bone and cartilage disorders such as degenerative arthritis. A survey conducted in 1977 reported that 88% of lameness in the UK was caused by problems in the hooves and only 12% caused by leg problems (Russell et al., 1982). Although this survey was conducted almost 30 years ago, most current research still focuses on hoof pathologies.

Current methods used to measure hoof and leg injuries or disease can be divided into either subjective or objective measures. Subjective measures typically rate injuries on a severity scale based on the density and extent of the lesion. For example, Greenough and Vermunt (1991) provide a 4-point scale to measure sole haemorrhages in dairy cattle: 1 = slight discoloration; 2 = moderate haemorrhage; 3 = severe haemorrhage; and 4 = exposed corium. The broad descriptions used for each category in these severity scales are open to interpretation and may result in poor repeatability between observers.

Some studies have provided more explicit descriptions within each category to improve consistency between observers. For example, Leach et al. (1998) used a scale that described the severity categories for sole haemorrhages and ulcers in dairy cows using descriptions of the intensity of coloration of blood in the tissue (see Table 1.2). When the authors tested the repeatability of this scoring system between 2 observers they reported a correlation coefficient of 0.83 and concluded that the descriptions provided for each category produced adequate repeatability. Repeatability of other severity scoring systems has not been tested to date (e.g., Greenough and Vermunt, 1991; Manske et al., 2002a). The issues of repeatability of subjective methods and between-observer consistency will be discussed in more detail later in this chapter (section 1.4.1).

Objective measures usually quantify the number of hoof and leg injuries that animals have. For example, Bell (2004) reported that of the 624 dairy cows examined in the Fraser Valley, British Columbia, 86% had at least 1 sole haemorrhage, and Leach et al. (1998) calculated that dairy cows in their study had between 7 and 28 lesions 9 wk after calving. One drawback of recording only the number of lesions is that size and severity are overlooked. Some studies have estimated the size of each lesion by photographing hooves and using image analysis to calculate the affected area. For example, the 247 sole haemorrhages recorded by Leach et al. (1998) covered on average 11% of each claw. Although this method of recording size is accurate and highly repeatable, it has not been used widely to date perhaps because of the time taken to collect the data.

Most studies of hoof and leg pathologies have collected both subjective and objective measures of injuries. The injury data have been reported either as a score for each hoof or as an overall injury score for each cow, but the way these scores are calculated differs from study to study and each method has its drawbacks. Some researchers have summed the severity scores on each hoof and reported an overall lesion score for each hoof separately (e.g., Vokey et al., 2001). However, with this approach, a hoof with 5 “mild” lesions would be given a higher score than a hoof with a single “severe” lesion, although the severe lesion might have a greater effect on the level of pain and ability to walk. Other researchers have included a component of lesion severity in their analysis. For example, Offer et al. (2000) reported the maximum lesion severity score for each hoof in their study. However, this method probably excludes valuable information. For instance, a cow with a “severe” lesion and a cow with a “severe” lesion and 5 “mild” lesions on the same hoof would receive the same score, even though the combination of lesions may have a greater effect on the animal. A more complicated approach is to combine the effects of size, severity and number into an overall injury score. For example, Leach et al. (1998) produced an overall lesion score by calculating the percentage area of the hoof affected by the lesion multiplied by an adjusted severity score. The authors then reported overall injury scores for cows by summing the overall lesion scores. In this study, an adjusted severity score was used to give lesions of higher severity more importance, even though it is not known whether more "severe" lesions are more painful than "mild" lesions.

One issue that previous authors have failed to consider is that the location of lesions on the hoof may also affect the animal. For example, a haemorrhage in the white line (the junction between the sole and the wall) may have different effects on the animal from a haemorrhage on the sole, as the composition of the horn and the forces applied in these 2 areas differ.

Ultimately, the way in which data on location, severity, number and size of lesions are treated should depend upon what these injuries mean to the animal. Is a cow with a sole ulcer affected more or less than a cow with 10 "mild" lesions? How big or severe does a lesion need to be before it is painful? Are some lesions not painful? To date, there is no research available to address these questions.

The methods described above record only external signs of injury. In some cases, however, evidence of injury or disease is not externally visible: examples include soft tissue lesions in the upper limb. In such cases, the typical diagnostic approach is to radiograph the limb, although usually producers would opt to cull animals before incurring expensive diagnostic methods and treatment (Blond et al., 2004). Apart from the 1 survey that reported 12% of lameness was caused by upper leg injuries (Russell et al. 1982), it is unclear how many cows are affected by such injuries today.

To summarize, a number of methods measure hoof and leg injuries and disease using variables such as the number, severity and size of lesions. However, researchers do not know how these variables, independently or in combination, relate to pain experienced by cows while walking or standing. We also need to understand how the location of injuries may affect cows, and develop improved methods of assessing hoof and leg injury and disease in living animals.

1.4 Measuring the effects of hoof and leg pathologies on gait

Not only have researchers used objective and subjective methods to record the presence and severity of hoof and leg injuries and disease in dairy cattle, they have also used these methods to measure the effects of hoof and leg pathologies on gait.

1.4.1 Subjective methods of gait assessment

Lameness researchers commonly use subjective observational methods to study the effect of hoof and leg pathologies on gait. Two main approaches are currently in use: numerical rating scores (NRS); and to a lesser extent, visual analogue scales (VAS). NRS rate individual cows, typically on a 5-point scale, for the presence or absence of certain behaviours and postures related to gait. The first NRS used in dairy cattle research was a 5-point scoring system with half scores developed by Manson and Leaver (1988), where scores were assigned by observers according to the criteria in Table 1.3. VAS, previously used by human patients to rate their level of pain (Scott and Huskisson, 1976), consist of a horizontal line with a description of the behavioural extremes at either end of the scale, for example “sound” and “could not be more lame”. An observer then marks on the line a position that represents the condition of the animal. Welsh et al. (1993) used VAS to assess foot rot in sheep through observations of animals trotting and argued that it was more sensitive than NRS because it allowed sheep to be measured on a continuous scale, rather than placing individuals into discrete units.

Although previous authors have attempted to use these methods to quantify lameness in general, an alternative approach is to adapt the methods to investigate how specific hoof and leg problems affect specific behaviours. For example, anecdotal information suggests that cows arch their back and abduct/adduct their hind limbs when lame (Morrow, 1966; Greenough et al., 1981) but no work to date has attempted to directly assess these attributes.

Although subjective methods may be suited for on-farm assessment (i.e., they can be conducted quickly on-site, require no technical equipment, and enable evaluators to provide an overall assessment of gait in large numbers of animals), it is important to recognize that these methods have some weaknesses. Because assessments are subjective they may show poor reliability, and there is little evidence to evaluate whether these measures are valid indicators of injury or disease.

Reliability

Martin and Bateson (1998) stated that the reliability of a variable is the extent to which the measure is precise and consistent. The reliability of subjective methods of gait assessment may be affected by the observer and by the scoring system.

Hollenbeck (1978) suggested that observers could affect the repeatability of a study in a number of ways. Firstly, repeatability can be influenced by sources of bias, such as errors by omission (e.g., failing to score a behaviour that occurred) or errors resulting from observer expectations (e.g., failing to score an animal as lame because the rest of the herd was healthy). Secondly, experience may influence repeatability. For example, Main et al. (2000) reported that the agreement of scores of experienced and inexperienced observers evaluating pigs with NRS was only 26 to 53%, whereas agreement between experienced observers was 94%; this difference suggests that the scoring system was not reliable when used by inexperienced observers. Finally, observer scores may change over time (Hollenbeck, 1978). Such "observer drift" is especially a problem for live observations, whereas researchers using video recordings can quantify drift by re-scoring the same tapes at different times.

The scoring system may also affect the repeatability of a study. Some scoring systems use very general terms to categorize animals, allowing much leeway among observers. For instance, Whay et al. (1997) described categories of an NRS as "sound, imperfect locomotion, mild lameness, moderate lameness and severe lameness", with no additional definitions for each category. Other scoring systems provide more detail for each category. For example, Kestin et al. (1992) used the terms "no detectable abnormality, slight defect, identifiable defect, obvious gait defect, severe gait defect, and incapable of sustained walking". The authors gave further details within each score such as "acceleration, manoeuvrability and speed were affected" or "acceleration, manoeuvrability and speed were severely affected", but here again both the categories and terminology are ambiguous, potentially reducing reliability.

One way to assess the reliability of the scoring system is through observer consistency, in other words the extent to which scores agree when assigned separately on 2 occasions by the same observer. For example, Kestin et al. (1992) reported a rank correlation of 0.72 for within-observer consistency for an NRS of broiler chickens. Garner et al. (2002), using a more explicit version of Kestin et al.'s (1992) system, reported much higher within-observer consistency with a correlation coefficient of 0.95. Although a number of factors varied between the studies, it seems likely that the use of more explicit criteria in each category enhanced within-observer consistency.

A second method of assessing reliability of scoring systems is between-observer repeatability, i.e., the extent to which scores of different observers agree. Winckler and Willen (2001b) reported only 68% agreement between 3 observers when evaluating the gait of dairy cattle using a 5-point NRS. However, most disagreements (30%) differed by only 1 category and the authors' claimed that these differences would not result in misjudging animals.

Validity

Even a measure showing excellent repeatability will be of little use if it relates poorly to the phenomenon of interest. Unfortunately, few studies have examined the validity of scoring systems and those that have attempted to do so vary in success. One method to evaluate the validity of gait assessments is to compare scores with measures of hoof and leg pathology. For example, Winckler and Willen (2001b) reported a correlation coefficient of 0.50 between NRS and sole haemorrhages and digital dermatitis of dairy cows. The variation in scores not attributable to these hoof problems may have been due to other, undiagnosed pathologies and to weaknesses with the NRS.

In conclusion, current scoring methods are subjective in nature with uncertain reliability and validity. Reliability of gait assessment methods can be influenced by observer biases, experience and drift. In addition, ambiguous terminology used in these scoring systems can also affect reliability and increase measurement error. Furthermore, little is known about how these scoring systems actually relate to underlying injuries and disease.

1.4.2 Objective methods of gait assessment

Objective measures of gait provided by kinetics and kinematics might avoid some of the issues described above, although little work using these techniques has been conducted on dairy cattle.

Kinetics is the study of the forces involved in motion (Hall, 1995). Typical kinetic studies in animal gait research use force plates or force recording shoes to obtain force data. Both devices use electronic force sensors to measure the ground reaction forces of an animal. The force data can provide information on horizontal and vertical forces exerted by hooves or feet in contact with the ground and have been used to assess forces involved in walking of dairy cows (Scott, 1988; Van der Tol et al., 2002).

Kinematics is the study of changes in position of body segments over time, without reference to the forces involved in motion (Hall, 1995). Small spheres are commonly attached to the skin at standard anatomical locations, and high-speed cinematography captures the movement of the animal. Video records are transferred to motion analysis software, capable of digitizing a sequence of movements automatically, and the data collected can provide information on linear and angular displacements, velocity and accelerations of each marker (e.g., Peham et al., 2001).

Both techniques have practical applications for research on the effects of hoof and leg pathologies on gait. For example, Rajkondawar et al. (2002) proposed that force plate systems could be installed on dairy farms and used as a tool to detect cows with hoof injuries, and Herlin and Drevemo (1997) used kinematic techniques to evaluate the long-term influence of management systems on the locomotion of dairy cows. The problems over repeatability, discussed earlier for subjective methods, should not be as serious for objective methods, and in any case repeatability is easily quantified. However, validity is still a concern. For example, a force plate system used by Rajkondawar et al. (2002) has been proposed as a tool for detection of lameness in dairy cattle, but it is not clear how the measures actually relate to injury even in a single limb, much less to multiple injuries in several limbs. Although Rajkondawar et al.'s (2002) study correlated the force plate measures of walking cattle with the presence of an arched back as the measure of lameness, the paper did not report how forces varied with known hoof and leg pathologies. A recent study by Neveux et al. (2006) investigated the weight distribution of standing cows using force plates. The authors found that cows with high hoof injury scores (a summation of the severity and number of injuries per cow) showed greater variation in weight bearing between their legs when standing compared to cows with no injuries. These results indicate that measures of forces (both of stationary and moving animals) are a promising approach to identify cows with hoof injuries, but further work is required to establish whether these systems can identify specific hoof and leg pathologies.

Objective methods can also be subject to technical difficulties that reduce the usefulness of this approach. One difficulty of force plate studies is the inability to control where the animal places its feet on the ground (Barrey, 1999). Merkens et al. (1985) reported that multiple attempts (average 2.9) were needed to provide adequate data on the force exerted by a single limb of a horse, and Corr et al. (2003), testing broiler chickens, required on average 10 attempts per bird before sufficient data had been collected. This creates challenges for researchers in terms of keeping animals walking and avoiding fatigue. One alternative is to use force-recording shoes that avoid the issue of foot placement on the force plate. Researchers have developed force-recording shoes for horses (Schamhardt et al., 1993; Barrey, 1999), but these are heavier and thicker than regular horseshoes and thus may shorten strides and swing phases, as well as increase the work needed to move the limbs (Roepstorff and Drevemo, 1993).

A difficulty of kinematic studies is that skin displacements during locomotion can limit the accuracy of measures (Barrey, 1999). For example, Van Weeren et al. (1988) quantified marker position errors in horses and reported displacements of ≤ 2 mm at the fetlock joint but up to 20 mm at the distal end of the tibia. Schamhardt et al. (1993) suggested using sites where skin movement is negligible, at the fetlock for example, but this approach might not detect problems higher up the limb, such as arthritis in the hip joint.

In conclusion, both kinetic and kinematic methods can quantify behaviours associated with hoof and leg injuries and disease. These objective methods are likely more repeatable than the subjective methods described earlier, but they are subject to similar concerns regarding validity and to some technical difficulties, even under relatively controlled laboratory conditions.

In summary, both subjective and objective gait measures provide information on how hoof and leg pathologies influence gait, but researchers need to be aware of the relative weaknesses of each method as they are currently used. Subjective methods are "farm-friendly"; they provide an immediate, on-site assessment and require no technical equipment, but can show poor within- and between-observer repeatability. Objective methods of gait assessment are "lab-friendly"; they provide accurate and reliable data, but require sophisticated technology, limiting their use on farms. Ultimately, the choice of measure or combination of measures will depend on the types of information they can provide on specific injuries and disease. To evaluate how these measures relate to specific injuries and diseases, within- and between-animal comparisons are needed.

1.5 Within- and between-animal comparisons

To understand how hoof and leg pathologies affect animals, researchers often compare gait variables of an animal before and directly after imposing some form of treatment; such comparisons are "within-animal". For example, Sedlbauer (2005) compared subjective gait assessments of cows both before and after treatment with an analgesic. Alternatively, the gait of an animal can be compared to that of other animals; these are "between-animal" comparisons. For example, Buchner et al. (1993) compared the vertical hip movements of sound horses with those of horses with hind limb lameness.

Both within- and between-animal tests can be affected by the measure's repeatability. If study animals do not respond consistently when tested on multiple occasions then treatment differences will be difficult to detect. Some evidence suggests that animals are not very consistent in the way they walk. For example, Corr et al. (2003) reported that the ground reaction forces exerted by individual hens varied considerably between multiple recordings of the same animal, and even when speed was accounted for coefficients of variation remained high (32-53%). Accurate recordings of gait characteristics often require multiple measures, and Corr et al. (1998) stated that a large number of tests would be required to calculate a particular individual's gait profile with even modest precision. Once a reasonable estimate of the number of recordings per animal can be achieved, what are the relative benefits of within- and between-animal comparisons?

1.5.1 Within-animal comparisons

Within-animal comparisons give researchers the ability to use the animal as its own control and thus avoid variation between animals. Many horse studies record measures of gait from a sound animal and then report changes in these variables after an injury has been "induced", either through injection or by a device attached to the hoof (Peloso et al., 1993; Gentle and Corr, 1995; Buchner et al., 1996; Keegan et al., 2001). One problem with this approach is to determine when animals are sound. This can be difficult particularly for dairy cows where sole injuries can take approximately 8 wk to become visible as haemorrhages or ulcers (Bergsten, 1994); hence researchers can never be sure that a cow is free from these injuries. Other studies have compared how the gait of animals with existing hoof or leg pathologies change after administration of pain-relieving drugs (Duncan et al., 1991; McGeown et al., 1999; Danbury et al., 2000; Rushen et al., 2006).

In both cases, researchers report changes in an animal's gait from its baseline levels but there are other potentially confounding factors that need to be taken into account. Cross-over experiments, where each animal is subject to treatments in succession (i.e., presence or absence of a hoof or leg pathology) can sometimes create an order effect that is confounded with treatment (Morris, 1999). This is a common problem for studies investigating hoof and leg pathologies because the animals used are often all started on the same treatment; in such cases researchers cannot distinguish the effect of treatment from the effects of treatment order and time. Experiments can be balanced for order (Martin and Bateson, 1998), but most work to date on hoof and leg pathologies has failed to recognize the effect of order in the experimental design (e.g., Peloso et al., 1993; Keegan et al., 2001). A better approach is to use a switchback design in which a cow may begin the trial lame, is then given an analgesic for a period of time, and then returns to the lame condition after the drug wears off (Sedlbauer, 2005). This design allows each animal to act as its own control and accounts for time effects (Morris, 1999). However, researchers need to allow sufficient time between treatments for the animal to fully recover from the previous condition to prevent any carry-over effects (Morris, 1999).

1.5.2 Between-animal comparisons

Another way to assess the effects of hoof and leg pathologies is to make direct comparisons between animals. For example, Herlin and Drevemo (1997) compared differences in the gait of individual Friesian dairy cows. However, differences in gait between animals may be due to body size, and most studies have not corrected for size differences in between-animal comparisons (Herlin and Drevemo, 1997; Peham et al., 2001; Reiter, 2002). One exception is a study by Corr et al. (2003) that expressed force data of walking broiler hens as a percentage of each hen's body weight, thus enabling comparisons between birds of different weights. However, body weights of ruminants, like cattle, are highly variable due to differences in gut and rumen fill. Measures such as leg length may be more appropriate to account for size differences in these animals, as such measures are less prone to such large fluctuations once cows are fully grown. The effects of cow size are discussed in more detail in section 1.6.1.

As discussed earlier (section 1.1) another source of error is to group all injuries and disease together when comparing lame with non-lame animals. For example, Buchner et al. (1993) compared kinematic data from a group of sound horses and a group of horses that had varying degrees of hind limb lameness. Although this research indicated that horses with hind limb problems walked differently from sound animals it did not specify how different hoof and leg pathologies affected an animal. A dairy cow with digital dermatitis, for instance, may walk differently from a cow with a sole ulcer.

By recording the different responses of animals with specific injuries and diseases of the hooves and legs, researchers can gain a better understanding of how these injuries and diseases affect cow gait. A useful first step would be to determine basic gait variables of animals apparently free from pathologies, such as stride length and duration. A second step would be to investigate how dairy cows respond to a single known injury such as a lesion on a specific limb. However, if such a study used the existing variation in the population, this approach would require very large sample sizes because animals with no hoof or leg pathologies are relatively rare. Also, as discussed previously, it is sometimes unclear whether animals are actually free from certain pathologies, particularly in the case of sole haemorrhages, which take approximately 8 wk to become visible in dairy cattle.

To summarize, studies investigating hoof and leg pathologies often compare gait variables either within animals, by observing changes before and after injury, or between animals, by comparing animals with and without hoof and leg pathologies. In such studies, scientists should take into account that animals can be variable in the way they walk, and multiple recordings are needed to account for this variability. Within-animal tests need to account for order effects and between-animal comparisons need to account for covariates known to affect gait, especially animal size.

1.6 Other methodological factors

Earlier in this chapter I described how hoof and leg pathologies can affect dairy cow gait (section 1.4). However, other factors, such as animal conformation and posture, may also play a role in how animals walk, and environmental factors, such as the walking surface, may also affect gait.

1.6.1 Animal factors and gait

Conformation and posture are 2 animal factors that may influence gait. Conformation refers to the physical dimensions and shape of a cow (Greenough et al., 1997), and is typically evaluated on a 9-point scale for both production traits (such as udder depth), and nonproduction traits (such as hoof angle). Cow conformation may affect a range of gait variables, such as stride length or speed. For instance, tall cows with long legs would likely have longer strides than smaller cows. In order to increase the ability to identify gait differences due to painful injuries, such size differences need to be minimized or controlled for. However, to date no cattle gait studies have incorporated this in their analysis. In the human literature, Pierrynowski and Galea (2001) showed that scaling gait variables by weight or leg length reduces inter-subject variation, but no scaling was necessary when sizes were similar (Pierrynowski and Galea, 2001). Thus comparisons of cows differing in size should include morphometric measures like leg length as covariates.

Posture may also affect cow gait. Posture refers to how a cow stands or moves, and is distinct from conformation (Greenough et al., 1997). An animal may assume a particular posture to relieve pain from a hoof injury. For example, Greenough et al. (1997) described that often when cows stand they may “camp back” or “camp forward”, referring to the position of the hind legs in relation to a vertical line drawn from the pelvis, as a strategy to relieve pain in the heel or toe. Cows may also assume a posture to adjust for mechanical influences, such as a full, heavy udder. For example, Greenough et al. (1981) speculated that a full udder might cause abduction or adduction of the hind legs in the swing phase of the stride. Swinging the legs probably helps avoid udder contact; however, no research has tested whether there are changes in cow gait in response to a full udder.

In summary, researchers need to consider that certain features of the cow affect how she will walk. In order to identify and characterize the gait of cows with and without injuries, variation due to other factors such as conformation and posture need to be minimized. Future work needs to understand the effects of posture on gait, such as how the udder influences cow movement, while also controlling for differences in size.

1.6.2 Flooring and gait

In Heleski et al.’s (2004) survey described earlier, the majority of respondents were concerned about dairy cattle lameness but in addition almost 85% of animal science faculty members were highly concerned about the effects of flooring on lameness in intensively farmed animals. Flooring, especially concrete surfaces, are a known risk factor in the development of hoof and leg injuries and disease in cattle (Wells et al., 1999; Vokey et al., 2001; Somers et al., 2005). For example, Somers et al. (2003) recorded higher incidences of hoof disorders for cows on concrete than on straw, and Vokey et al. (2001) found higher sole haemorrhage scores for cows housed on concrete than on rubber.

Although it is recognized that flooring can cause hoof pathologies, little is known about the immediate effects of flooring on gait. Some basic work has demonstrated that certain characteristics of flooring, such as friction and firmness, may modify how cows walk. For example, Phillips and Morris (2001) reported that dairy cows walking on low friction surfaces took frequent, short strides compared to high friction surfaces (0.65 vs. 0.59 strides/s; 1.30 vs. 1.36 m, respectively) and Dijkman and Lawrence (1997) found that cattle walked more slowly in 30 cm deep mud than on concrete (0.81 vs. 1.05 m/s).

Recently, rubber has been introduced as an alternative flooring surface in dairy barns and although the benefits to long-term hoof health may be apparent, little is known about how rubber affects cow mobility. Only 1 study so far has investigated this, testing cows walking on solid and slatted concrete, solid and slatted rubber and wet, compressed sand (Telezenkho and Bergsten, 2005). Cow gait, assessed using a 4-point gait scoring system, was also included in the analysis. The authors concluded that rubber mats had a positive effect on locomotion, regardless of gait score, although their study was unable to balance for treatment order.

Clearly more detailed studies on the effects of rubber flooring on gait are needed before recommendations can be made. Furthermore, given that there is some evidence that cows walk differently on different surfaces, the influence of flooring on gait should be considered especially for those conducting gait assessments on different farms.

To summarize, differences in conformation, size, and flooring may account for some of the variation in the way cows walk. Research is needed to tease apart these effects on animal gait from any effects of hoof and leg pathologies.

1.7 General conclusions

It is clear that hoof and leg pathologies are important to the welfare of dairy cows and the profitability of farms. However, given the extent of literature on lameness in dairy cattle published over the last 25 years, it is surprising that several fundamental issues remain to be addressed. Basic questions such as how do healthy cows walk, how do cows with hoof injuries and disease walk, and are the current measures of gait valid and reliable, have not been addressed. Once these basic questions have been tackled researchers can start to investigate the influence of other variables, such as udder size and flooring surface, on gait. The aim of my thesis was firstly to investigate the assessment of gait in dairy cattle with and without hoof pathologies and secondly, to examine variables that may affect gait. I have addressed these aims in Chapters 2 through 5 of this thesis:

1. In Chapter 2 I describe the walking gait profile of cows with no visible signs of hoof pathology using kinematic gait analysis, compare this with profiles of cows with sole haemorrhages and cows with sole ulcers, and determine which basic stride variables are valid indicators of hoof pathologies.
2. In Chapter 3 I describe the walking gait profile of cows with no visible signs of hoof pathology using an explicit gait scoring system, compare this with gait profiles of cows with sole haemorrhages and cows with sole ulcers, and determine which gait-associated behaviours are valid indicators of hoof pathologies and can be scored consistently.
3. In Chapter 4 I examine how udder fill influences cow gait, using the valid and reliable measures identified in Chapters 2 and 3, and compare this effect for cows with and without hoof injuries.
4. In Chapter 5 I assess the effects of flooring surface on cow gait, using the valid and reliable measures identified in Chapters 2 and 3, and compare these effects for cows with and without hoof injuries.

Table 1.1 Prevalence and incidence of hoof lesions in dairy cattle. Prevalence is defined as the number of cows affected divided by the total number of cows at risk at one time; incidence is defined as the number of new cases over a period of time. Studies are from 2000 onwards.

Country	Sample size	Prevalence	Incidence	Reference
U.K.	5 herds/900 cows		69 new cases per 100 cows per year	Hedges et al. (2001)
Sweden	101 herds/4899 cows	72%		Manske et al. (2002b)
The Netherlands	47 herds/3190 cows	80%		Somers et al. (2003)
Canada	20 herds/624 cows	86%		Bell (2004)

Table 1.2 A system for scoring severity of sole haemorrhages and ulcers in dairy cattle (from Leach et al., 1998).

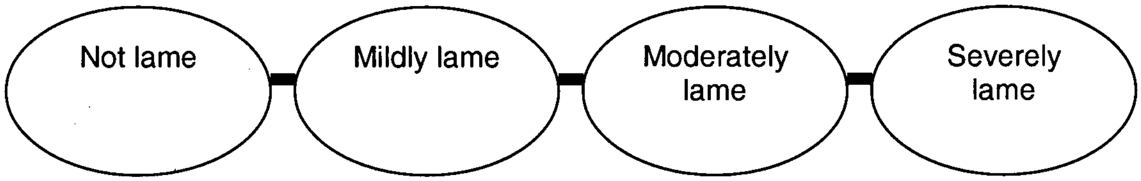
Injury	Score	Description
Haemorrhage	1	Diffuse red or yellow in horn
	2	Stronger red colouration
	3	Deep dense red
	4	Port colouration
	5	Red raw, possibly fresh blood
Ulcer	6	Corium exposed
	7	Severe sole ulcer with major loss of horn
	8	Infected sole ulcer

Table 1.3 A numerical rating system (NRS) for dairy cattle locomotion (from Manson and Leaver, 1988).

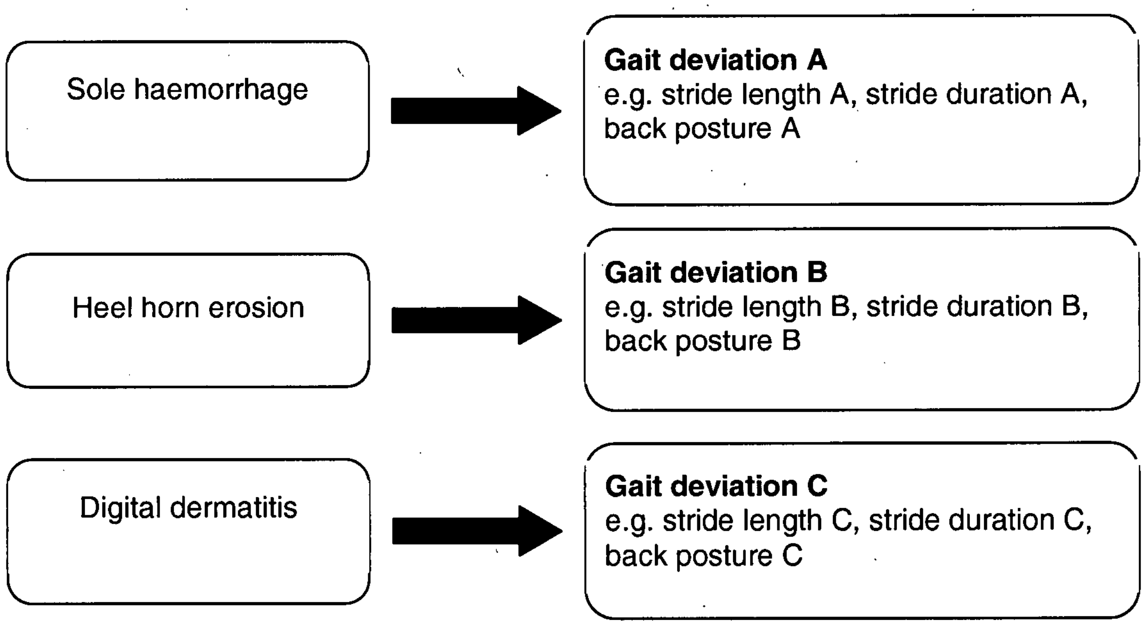
Score	Description
1.0	Minimal abduction/adduction, no unevenness of gait, no tenderness
1.5	Slight abduction/adduction, no unevenness or tenderness
2.0	Abduction/adduction present, uneven gait, perhaps tender
2.5	Abduction/adduction present, uneven gait, tenderness of feet
3.0	Slight lameness, not affecting behaviour
3.5	Obvious lameness, some difficulty in turning, behaviour pattern affected
4.0	Obvious lameness, difficulty in turning, behaviour pattern affected
4.5	Some difficulty in rising, difficulty in walking, behaviour pattern affected
5.0	Extreme difficulty in rising, difficulty in walking, adverse effects on behaviour pattern

Figure 1.1 Two conceptual models of lameness.

a) A scaling approach quantifying lameness on a one-dimensional scale



b) A classificatory approach that identifies specific hoof and leg pathologies and the consequent effects on cow gait



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CHAPTER 2: Hoof Pathologies Influence Kinematic Measures of Dairy Cow Gait[1]

2.1 Introduction

In recent years, hoof pathologies have become a focus of research for those concerned with the welfare and productivity of dairy cattle. Studies indicate an increase in the incidence of injuries over the last 25 yr, from 5.5% of dairy cattle in 1977 (Russell et al., 1982) to as much as 55% in 1991 (Clarkson et al., 1996). Hoof pathologies are of concern not only because of the large number of cows affected, but also because their health is compromised, pain may be experienced, and often cows spend less time feeding resulting in loss of weight and body condition (O'Callaghan, 2002). In addition, economic costs to producers can be great given the high incidence and cost in lost milk production per cow. Recent studies estimated that over 300 kg of milk is lost per cow per year as a result of hoof injuries (Warnick et al., 2001; Green et al., 2002).

Ultimately, negative effects on both the welfare and productivity of dairy cattle can be reduced by improving early detection and treatment of hoof pathologies. However, early detection is often difficult, because dairy cattle tend to show little overt behavioural response until injuries are advanced (O'Callaghan, 2002) and many cases may persist for months before identification and treatment. To date, there are 2 main approaches to detection of hoof pathologies in research studies. One is to measure the outcome of injuries through behavioural observations of cows with impaired gait (Manson and Leaver, 1988; Sprecher et al., 1997). This approach, however, suffers from a lack of well-defined standards, and relies on the skill of the observer to detect subtle gait abnormalities (Keegan et al., 1998). Significant variation exists both within and between observers probably because of the subjective nature of this approach. For example, O'Callaghan et al. (2003) reported that when an observer scored the gait of the same cows on 3 separate days only 56% of scores were identical; and only 37% agreement

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was reached between 2 observers scoring the same cows on the same day. A second approach is to score injuries on the hooves (Greenough and Vermunt, 1991). However, injuries such as sole haemorrhages (**SH**) generally reflect damage incurred months before, and although lesions may be visible, it is not clear whether all are painful.

Biomechanical techniques, including kinematics, can be used to measure cattle gait, and could provide an accurate and objective method of analyzing alterations in hoof movements that may be precursors to clinical lameness. Although kinematic gait analysis has been used extensively in research on horses (Barrey, 1999), this approach has rarely been applied to cow locomotion. Other biomechanical techniques are available to study gait, including force platforms, electromyography, and accelerometers. Kinematics, however, provides a non-invasive technique that also minimizes cow handling. One study calculated basic kinematic measures including stride duration, speed, and joint angulations of cows managed in tie-stall, loose-housed and pasture systems and found that some restrictions in joint movement were evident in those cows kept indoors (Herlin and Drevemo, 1997). More recently, Ceballos et al. (2004) used kinematic techniques to determine spatial requirements of cattle during lying-down with the aim of making recommendations for better stall design. Those authors concluded that kinematic techniques provided an accurate method of assessing cow movement. To our knowledge, however, no previous work using computer-aided kinematic techniques exists to evaluate dairy cattle movement for studying the effects of hoof pathologies.

Two common hoof pathologies found in North America and Europe are SH and sole ulcers (**SU**; Manske et al., 2002; Somers et al., 2003; Bell, 2004). We hypothesized that these hoof pathologies affect kinematic measures of cow gait. The specific aim of this study was to describe the walking gait profile of cows with no visible injuries and compare this with the profiles of cows having SH and SU.

2.2 Materials and methods

2.2.1 Cows and management

This study was conducted on 48 high-producing loose-housed Holstein dairy cows at the University of British Columbia's Dairy Education and Research Centre in Agassiz, Canada. Individual cows were selected randomly with the constraint that 24 primiparous (mean 99 DIM; BCS = 2 to 3) and 24 multiparous cows (parity = 2 to 7; mean 73 DIM; BCS = 2 to 3) were used. At the start of the study, primiparous and multiparous cows produced on average 28.5 ± 4.3 and 50.4 ± 7.3 kg/d of milk, respectively. Cows were fed twice daily a TMR diet formulated to meet or exceed NRC (2001) requirements for lactating dairy cows. Water was freely available from self-filling troughs. Stalls were deep bedded with 0.40 m of sand. Flooring within 1.85 m of the feed bunk was grooved 2.5 cm-thick rubber. Elsewhere in the pen, flooring was grooved concrete. Cows were milked twice daily in the parlour at 0500 and 1600 h. Cows were cared for according to the standards of the Canadian Council on Animal Care and a protocol approved by the University of British Columbia's Animal Care Committee.

2.2.2 Data collection

Video recordings

Every day for 4 wk before initiating data collection, cows were walked along a 40-m grooved concrete test alley to and from the milking parlour. A rope barrier was used to mark a 1.15 m wide path, forcing cows to walk in a straight line with minimal side-to-side movement and in single file. The cows were allocated to 2 groups for management purposes. The first group of 24 cows was filmed after morning milking (between 0540 h and 0810 h) for 7 consecutive days and then the procedure was repeated on the second group of 24 cows during the next 7 d. Before each day of recording, the test alley was cleaned with automatic scrapers.

A video camera (Panasonic AG-195MP, Matsushita Electric, Mississauga, ON, Canada), recording at 60 frames per s, was fixed in position 6.75 m perpendicular to the line of movement of the cows. A 100-W light was attached above the camera and directed at the test alley. The camera was able to capture cows walking the mid-section of the test alley (length 7.05 m).

Cows had a reflective marker, visible from all angles, wrapped around the entire circumference of each leg directly above the metacarpo- and metatarsophalangeal joints. Markers were attached to the cows in the milking parlour 24 h before the first recording day to allow for habituation and were removed at the end of the 7-d recording period. Markers were made of reflective tape (0.04 × 0.22 m) backed with black cloth (0.15 × 0.22 m). The back wall of the test alley was also black to provide contrast for digitizing the video. At every recording session, at least 2 consecutive strides were recorded per cow, with the camera recording all 4 hooves from the left lateral side. Cows walked in small groups (2 to 6 individuals) during the recording session and the order and position of cows was noted. At each recording session, spatial calibration of every video clip was performed to allow the data to be converted into metric units. A meter ruler with 0.05 m of reflective tape attached at each end was held in the middle of the test alley, and calibrated using a custom calibration program in PEAK Motus 3.2 (Peak Performance Technologies, Inc., Englewood, CO). Accuracy of marker position within the calibrated field was determined to be 1 mm in the sagittal plane.

One observer digitized all cow locomotion using the PEAK system. Video recordings when cows were observed to stop, stumble, slip, defecate, urinate or perform any gait other than walking were not digitized. Furthermore, recordings were not digitized if reflective markers were missing, or if a cow walking in a group was sufficiently close to the cow in front that her head was lowered and moved from side to side.

Hoof strike (**HS**) and hoof-off (**HO**) events were defined visually from the video recordings by the observer. Hoof strike occurred when the hoof was first observed contacting the ground at the beginning of the stance phase. Hoof-off occurred when the hoof was first observed leaving the ground at the end of the stance phase. Digitized data were smoothed using a fourth order, zero lag Butterworth filter at a cut-off frequency of 6 Hz (Winter, 1991). From the co-ordinate data, 6 stride variables were calculated for each hoof as defined in Table 2.1.

Clinical assessment of hooves

Previous research has reported that SH and SU take 8 wk to become visible on the sole of the hoof (Bergsten and Herlin, 1996). As the aim of this study was to look at the effects of SH and SU on gait, a professional hoof trimmer trimmed the front and hind hooves of each cow 8 to 9 wk after the trial. An experienced observer examined each hoof and recorded the presence of SH using a modified version of Greenough and Vermunt's (1991) lesion scoring system. Number, location, and severity of SH on each hoof were scored on a 4-point scale [1 = slight discoloration; 2 = moderate hemorrhagic lesion; 3 = severe hemorrhagic lesion; 4 = sole ulcer (exposed corium)]. At this time the presence and location of other foot pathologies such as digital dermatitis, interdigital hyperplasia, and interdigital necrobacillosis was also noted.

Hoof health data of 2 cows were not collected because the cows were dropped from the trial due to coliform mastitis and early dry off for management reasons. Of the 46 cows examined, 63% had hoof pathologies at the time of hoof examination. The presence of digital dermatitis was noted on 8 cows, but we could not be certain whether this was present at the time of video recording so these animals were dropped from the analysis. The remaining 38 cows were grouped into 3 mutually exclusive hoof health categories: healthy cows with no visible signs of injury or disease on hooves (n = 17); cows having only SH (n = 14); and SU cows having exposed corium and SH (n = 7). No cases of interdigital hyperplasia or interdigital necrobacillosis were recorded.

Morphometric measures

Individual cow body mass was recorded twice during the trial, with 1 wk between recordings. Mean body mass (± SD) of healthy (582 kg ± 72), SH (620 kg ± 58), and SU (676 kg ± 68) animals differed ($P < 0.05$) among groups, a difference that was largely due to a 778 kg cow in the SU group. All statistical analyses reported below were conducted with and without this cow. In no case did the inclusion of this data affect the significance of the results reported, so results described below include this cow.

Nine months after the video recordings, 3 additional morphometric measures were recorded from the 26 cows still available in the herd. Measurements were height at the withers (T3), height at the tailbone (Cc1) and the length of the back (Cc1 - T3). All measures were recorded 3 times for each cow from the left lateral side. Measures were only recorded when cows were standing with their head elevated and legs straight. No differences were detected among groups for any of these 3 measures (Table 2.2).

2.2.3 Statistical analyses

Using the first stride per day, we calculated mean stride variables by averaging across the 4 hooves and 7 d of video recordings for each cow. Differences between the 3 hoof health groups for the stride variables described in Table 2.1 (stride length, stride height, stride duration, stance duration, swing duration, and hoof speed) were tested using a one-way ANOVA (SAS Inst. Inc. Cary, NC). To address the specific aims outlined in the introduction, we employed contrast statements to test for differences between healthy cows and cows with SH (1 df), and SU (1 df).

2.3 Results

2.3.1 Stride variables

Compared with the healthy group, cows with SU had shorter strides, and during the swing phase, hooves were not raised as high (Table 2.3). Total stride duration of cows with SU was longer than that of healthy cows. Furthermore, cows having SU spent on average 0.22 s longer with hooves in ground contact (stance duration) and had a slower average hoof speed than healthy cows (0.90 vs. 1.11 m/s, respectively). No differences were detected between the healthy and SH groups for any spatial or temporal stride variables. As older cows are more susceptible to injuries, we reanalyzed the data considering only multiparous cows. As with the analysis considering all cows, multiparous cows having SU ($n = 6$) differed from healthy cows ($n = 5$) in stride length, height, stride duration, stance duration and speed ($P < 0.05$).

Stance and swing durations of cows should not only be considered in absolute values, but also as a proportion of the total stride duration. For example, healthy and SU cows had the same absolute swing durations (0.57 s), but as a percentage of stride duration there was a difference in swing (45 and 39%, respectively) between the 2 groups. The stride cycle (Figure 2.1a; b) for healthy and SU cows illustrates the stance and swing durations as a proportion of the stride. The HS and HO sequence for each hoof and the number of hooves in ground contact (i.e., double or triple support) is also shown. During the periods of double support, cows alternated between ipsilateral (same side) and diagonal support. Given that the stride variables of SU cows were significantly different from healthy cows, we tested for differences between the proportion of triple support in the strides of healthy cows and those having SU. Healthy cows (Figure 2.1a) spent only 18% of the stride in triple support, but this more than doubled (42% of the stride; $P < 0.001$) for cows with SU (Figure 2.1b).

2.3.2 Hoof movement

For descriptive purposes, hoof trajectories of front and rear hooves (i.e., changes in horizontal and vertical displacement over time) are illustrated in Figure 2.2. This descriptive analysis corresponds well with the averages and treatment differences described in Table 2.3. Animals with SU have shorter strides and hooves are not raised as high, although this difference appears more pronounced for the rear hooves. In addition, it is interesting to note that for all hoof health groups the front hoof height peaked twice during the swing phase (HO-HS); once shortly after HO, and once before HS.

Individual differences in the type, number, and location of hoof pathologies can complicate comparisons of hoof trajectories. For example, Cow 13 had a SU on the right rear hoof combined with minor SH on the left front and left rear hooves, 3 moderate SH on the rear hooves, and 1 severe SH on the right front hoof. The hoof trajectories of this cow were markedly different from healthy cows (Figure 2.3). The ulcerated right rear hoof not only showed a shorter stride length and a lower maximum stride height, but the stride also reached maximum height earlier than that of healthy cows.

2.4 Discussion

This is the first study to measure the gait of healthy cows and those with hoof pathologies using computer-aided kinematic techniques. Some basic stride measures from this study show good agreement with previous kinematic literature on cow gait. For example, Herlin and Drevemo (1997) reported a mean stride duration for dairy cows of 1.22 s compared with 1.26 s for the healthy cows in the current study. However, some stride variables were different to those previously reported. Healthy cows in our study had longer stride lengths (1.40 vs. 1.34 m) and faster walking speeds (1.11 vs. 0.80 m/s) than those reported by Phillips and Morris (2000). However, Phillips and Morris (2000) did not report on hoof health of their cows. Another interesting finding of this study was the difference in hoof trajectory patterns between front and rear hooves of both healthy cows and those with hoof injuries. This difference in hoof trajectory is probably due to the difference in structural anatomy of the front and rear legs, but further work is required to determine how this relates to the trajectories observed.

Kinematic measures were effective at identifying cows having SU: stride length, height, duration, and speed were all different from healthy cows. Sole ulcers are considered painful (Whay et al., 1998), and it is likely that cows with these injuries reduce loading on the affected limb. In the present study, cows having SU both shortened their strides and walked more slowly than healthy cows. By slowing the speed of each hoof, the loading of the affected limb should be more gradual and reduce the peak forces, or impact, at the time the hoof hits the ground (Buchner et al., 1996). One study in cattle (Scott, 1989) and another in horses (Hood et al., 2001) measured forces in walking lame and non-lame animals and found that the loading was often reduced on affected limbs.

The stride cycle, with alternating sequence of diagonal and ipsilateral limb use, and the pattern of double and triple support observed in this study, was originally described by Gambaryan (1974). The current study is the first to quantify kinematically the stride cycle for cattle, and provides a unique contribution to the field of dairy cattle lameness by comparing the cycle for cows with and without SU. Cows having SU increased the proportion of triple support during the stride (42 vs. 18%) and had longer stance times (0.91 vs. 0.69 s) compared with healthy cows. These results also support the idea that cows having injuries such as SU may try to reduce the loading on an injured limb by distributing the load between 3 legs for as much time as possible. More detailed studies of limb loading in cattle, including force plate data, are needed to more fully understand how cows respond to hoof injuries.

Stride height of cows having SU was less than healthy individuals, but the reason for this difference is unclear. Differences in stride height have also been observed in horse studies. For example, Stashak (2002) reported that the stride height of lame horses was lower than non-lame horses, but an explanation for this difference was not provided.

No significant differences were found between stride variables of healthy cows and those having SH. It could be that less severe injuries, such as minor SH, are not painful enough to alter gait. Indeed, Whay et al. (1997) investigated the relationship between SH, nociception and a qualitative measure of gait in dairy cattle, and reported that only cows having more severe SH had abnormal gait. Alternatively, changes in gait may only occur when injuries are located in the weight-bearing zone of the hoof. Corr et al. (1998) found that broiler birds housed on mesh flooring often had foot lesions on the metatarsal pad. The authors suggested that this normally non-weight-bearing part of the foot had a lower threshold to pressure damage than other areas of the foot. Van der Tol et al. (2002) reported that the greatest plantar pressures in the dairy cow hoof were on the sole. In this study, 71% of cows in the SH group had lesions on the sole. Future research may help to identify which sites of injury are important in dairy cow gait, but this will require reasonable sample sizes for different injuries in different locations.

Location, number, and severity of injuries varied among cows in this study. For example, in the SH group, lesions were located on the left front hoof for some cows and on the right rear hoof for others. Almost two-thirds of cows with hoof pathologies had more than 1 injury and nearly half of the SH cows had moderate to severe haemorrhages. Averaging across affected and unaffected hooves may have masked differences among group gait profiles. Hoof trajectories of 1 cow (Cow 13) were used to illustrate that multiple injuries may affect gait in a number of ways. The right rear hoof trajectory of this cow was shortened and lowered, probably due to the presence of a sole ulcer on this hoof. It is more difficult to explain, however, the altered left front hoof trajectory, as only a minor SH was observed on this hoof. Future research needs to investigate how cows alter their gait in response to a single painful injury before attempting to predict responses to injuries in multiple locations.

The variable time course of injury development may have increased variation in the current study. In this study, the presence of injuries at the time of video recording was determined through hoof examinations 8 to 9 wk after the end of the trial, but this may not have captured all injuries. Another potential source of variation in the current study is that cows were allowed to walk at their natural pace. Walking speed is in itself an interesting measure, but it likely affects other stride variables. Future work using treadmills could control walking speed.

It is evident from the results of this study that kinematic gait analysis is an objective and accurate research tool, able to identify cows having SU. At this stage, kinematic gait analysis is likely impractical for use on commercial farms, but technological advances, such as marker-free systems (Green et al., 2000), would facilitate such applications in the future.

In conclusion, analyses of cow gait using kinematic techniques showed distinct differences among cows with no visible hoof pathologies and those with painful injuries such as SU. This study demonstrated that cows with SU altered their gait in an apparent attempt to reduce loading the affected leg for as long as possible during the stride cycle. More detailed analysis is needed to see if other pathologies also have characteristic effects on gait that could be useful in early detection of lameness.

Table 2.1 Description of stride variables calculated from kinematic measurements.

Variables	Description
Spatial	
Stride length, cm	Horizontal displacement between 2 consecutive hoof strikes of the same hoof
Maximum stride height, cm	Maximum vertical displacement between 2 consecutive hoof strikes of the same hoof
Temporal	
Stride duration, s	Time interval between 2 consecutive hoof strikes of the same hoof
Stance duration, s	Time the hoof is in contact with the ground (interval between hoof strike and following hoof-off)
Swing duration, s	Time the hoof is not in contact with the ground (interval between hoof-off and following hoof strike)
Hoof speed, m/s	Stride length/stride duration

Table 2.2 Mean (± SD) morphometric measures of cow height and length.

Measure	Healthy (n = 9)	Sole haemorrhages (n = 13)	Sole ulcers (n = 4)
Height at withers, cm	141 ± 5	139 ± 3	144 ± 1
Height at tailbone, cm	145 ± 4	144 ± 4	144 ± 2
Length of back, cm	143 ± 4	142 ± 3	144 ± 2

Table 2.3 Least squares means (± SEM) of spatial and temporal stride variables for healthy cows (n = 17) and those with sole haemorrhages (SH; n = 14), and sole ulcers (SU; n = 7).

Variable	Hoof condition	Mean ± SEM
Spatial		
Stride length, cm	Healthy	139.5 ± 2.1
	SH	139.3 ± 2.3
	SU	130.0 ± 3.2 *
Maximum stride height, cm	Healthy	9.6 ± 0.2
	SH	9.7 ± 0.2
	SU	8.7 ± 0.3 *
Temporal		
Stride duration, s	Healthy	1.26 ± 0.03
	SH	1.30 ± 0.04
	SU	1.48 ± 0.05 ***
Stance duration, s	Healthy	0.69 ± 0.03
	SH	0.75 ± 0.03
	SU	0.91 ± 0.04 ***
Swing duration, s	Healthy	0.57 ± 0.01
	SH	0.55 ± 0.01
	SU	0.57 ± 0.02
Hoof speed, m/s	Healthy	1.11 ± 0.03
	SH	1.08 ± 0.03
	SU	0.90 ± 0.05 ***

*Different ($P < 0.05$) from healthy cows; **Different ($P < 0.01$) from healthy cows; ***Different ($P < 0.001$) from healthy cows.

Figure 2.1a The mean proportion of double and triple support during a single stride [either from hoof strike (HS) to HS or from hoof-off (HO) to HO] for each leg for healthy cows (n = 17); RF = right front hoof, LF = left front hoof, LR = left rear hoof, RR = right rear hoof.

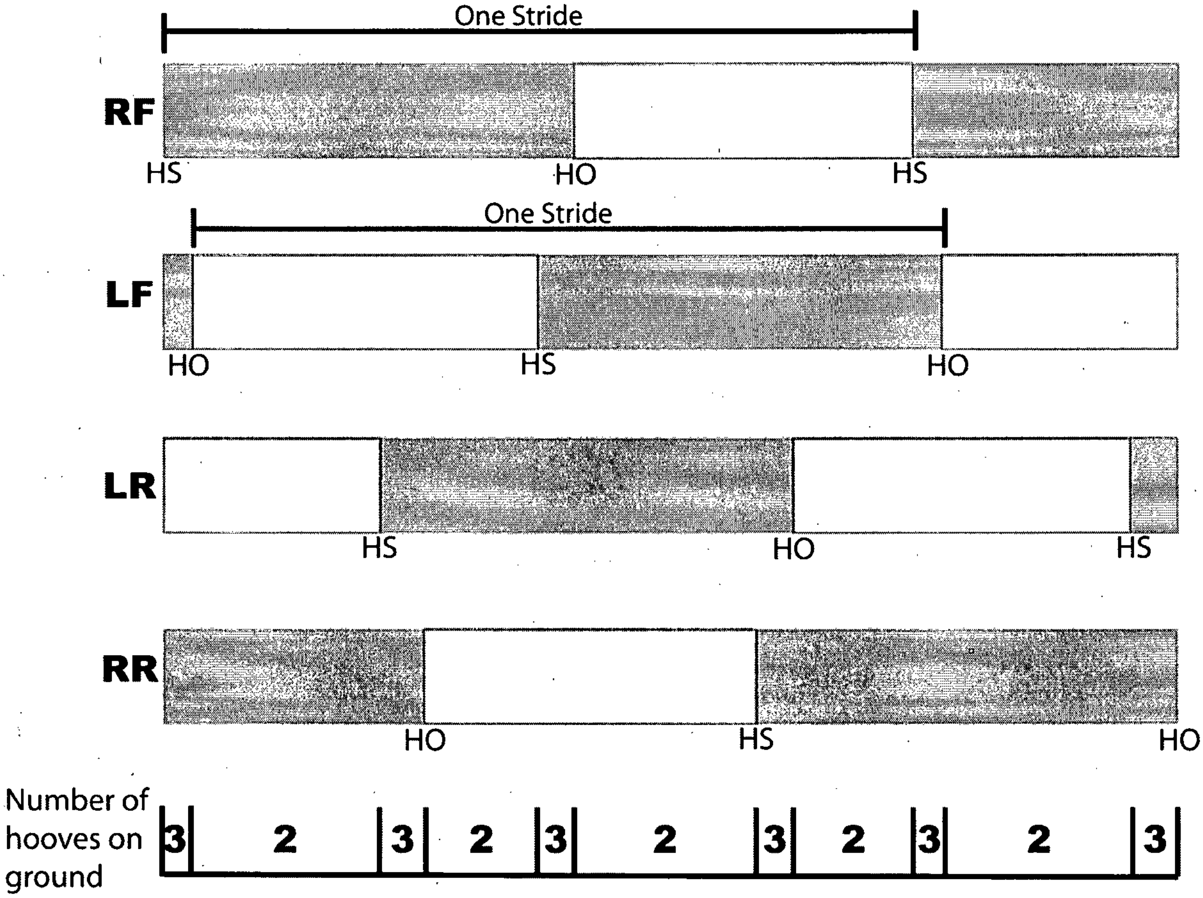


Figure 2.1b The mean proportion of double and triple support during a single stride [either from hoof strike (HS) to HS or from hoof-off (HO) to HO] for each leg for cows (n = 7) with sole ulcers; RF = right front hoof, LF = left front hoof, LR = left rear hoof, RR = right rear hoof.

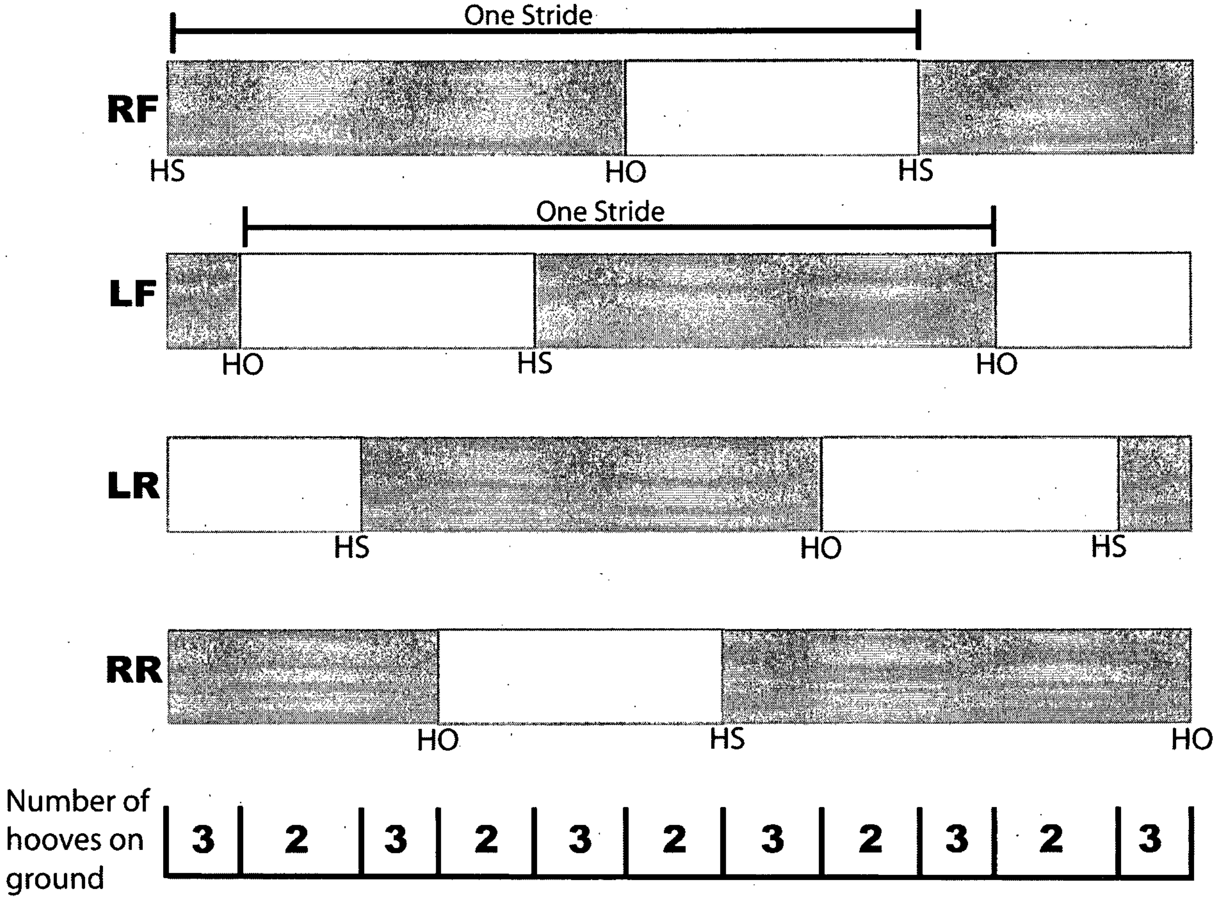


Figure 2.2 Mean trajectories of the left front and left rear hoof during the swing phase based on an average stride per cow calculated for healthy cows (□), cows having sole haemorrhages (▲), sole ulcers (×).

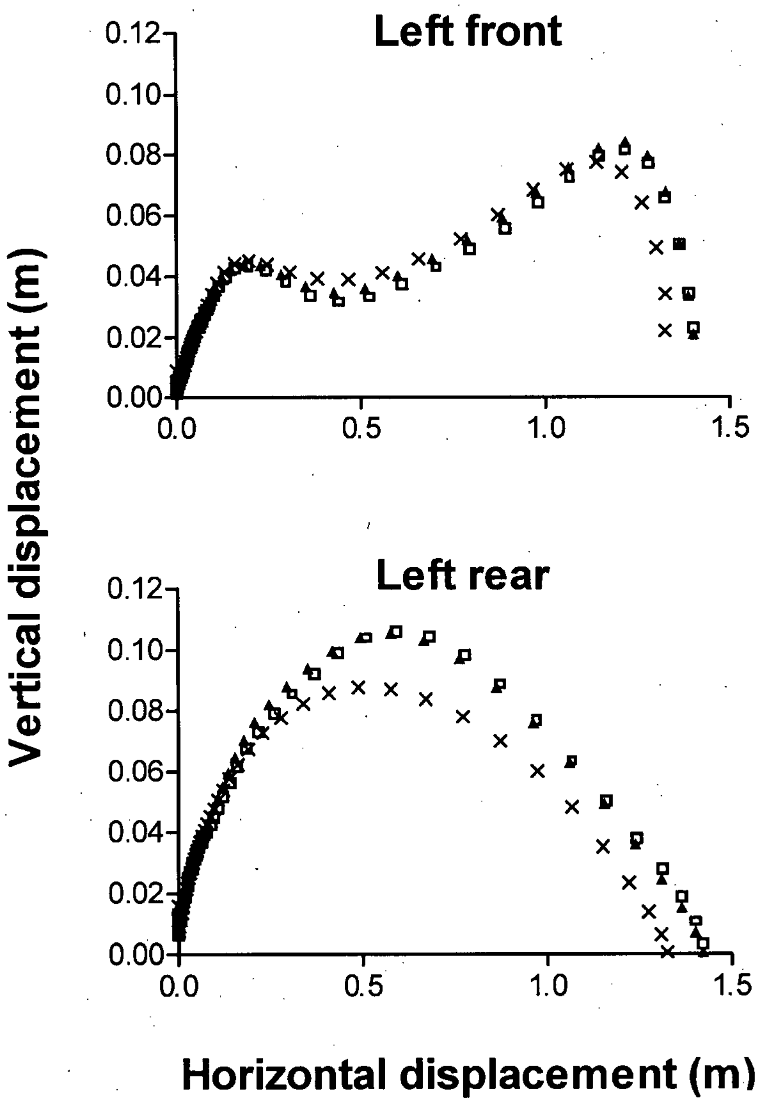
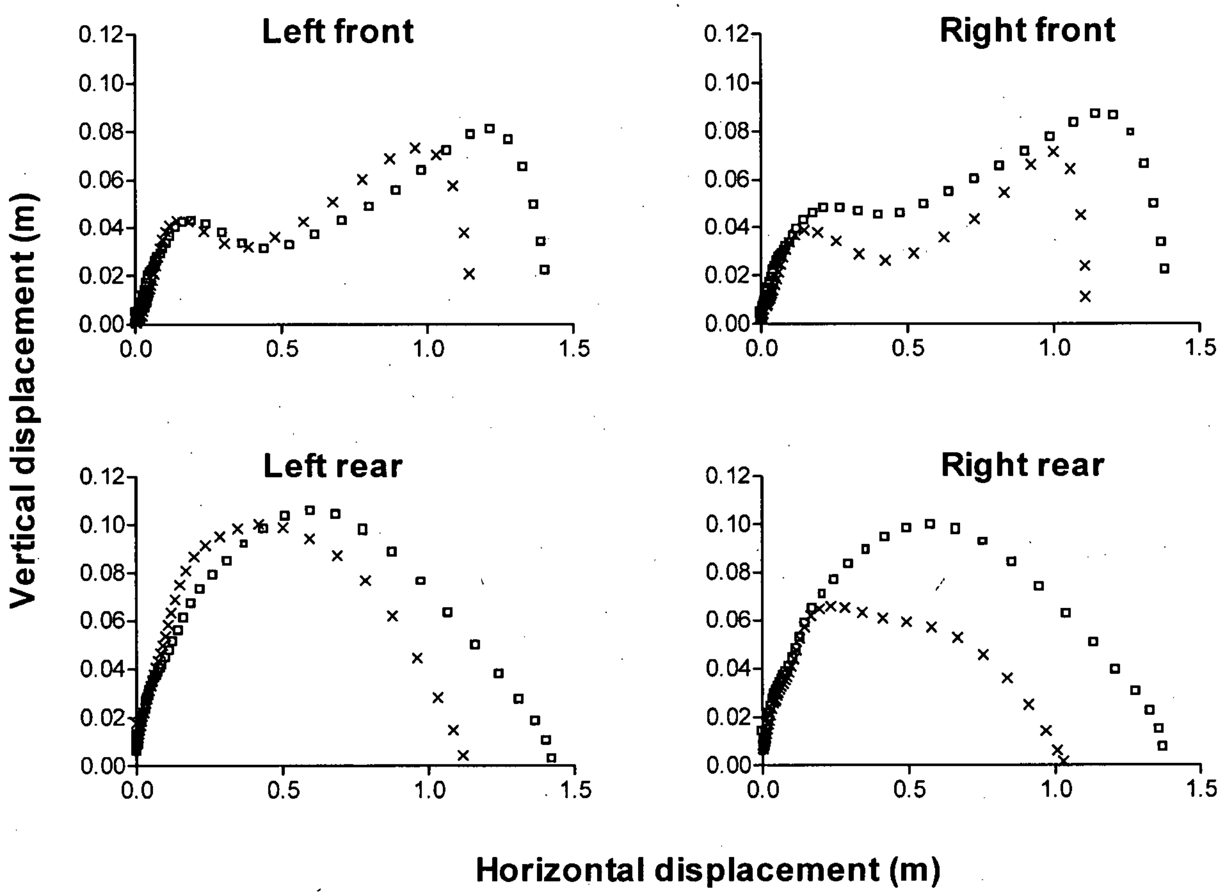


Figure 2.3 Mean hoof trajectories for Cow 13 (×) and healthy cows (□; n = 17) during the swing phase, shown separately for each of 4 hooves.



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CHAPTER 3: Effect of Hoof Pathologies on Subjective Assessments of Dairy Cow Gait[2]

3.1 Introduction

Lameness is recognized as a source of economic loss for producers and pain and discomfort for cows (Russell et al., 1982; Warnick et al., 2001; Green et al., 2002). Current literature indicates that producers find it difficult to identify cows at early stages of lameness, because cattle tend to show little overt behavioural response until injuries are advanced (O'Callaghan, 2002). Whay et al. (2003) reported that producers were able to detect only 25% of lame cows, and Mill and Ward (1994) found that 13 of 15 producers could only identify lame cows that showed an obvious limp. Rather than identifying cows at these more severe stages of lameness, when costs of treatment are high and recovery is slow, methods are required to identify them at the early stages of lameness.

The most commonly used approach to detect lame cows is to assess some aspect of their walking gait. Several different systems exist, often termed lameness or locomotion scoring systems, such as those developed by Manson and Leaver (1988) and Sprecher et al. (1997). These scoring systems rate the gait of animals, typically on a 1 to 5 scale, for the presence or absence of certain behaviours and postures thought to be indicative of lameness (Manson and Leaver, 1988; Kestin et al., 1992; Welsh et al., 1993; Sprecher et al., 1997).

Usefulness of any assessment method is limited by its validity, reliability, and sensitivity. Little is known, however, about how gait-scoring systems for cattle perform in relation to these criteria. One way to evaluate the validity of an assessment method is to simply compare scores of cows with and without known pathologies. Those studies that have attempted to examine the validity of gait scoring systems report poor relationships between scores and measures of hoof and leg injuries or disease. For example, in one study, the presence of sole lesions accounted

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for only 22% of the variation in gait scores (Van Eerdenburg et al., 2003), and in another, the presence of known injuries accounted for 48% of the variance in gait scores (Whay et al., 1997).

As with any subjective technique, scoring systems can vary in reliability. Even the same observer may not score the gait of a cow the same on 2 occasions. For example, O'Callaghan et al. (2003) reported that a trained observer re-scoring the gait of 129 cows was consistent for only 56% of observations. In addition, a lack of agreement between observers has also been reported; O'Callaghan et al. (2003) found only 37% agreement in the scores of 2 observers, and Winckler and Willen (2001) found 68% agreement in scores of 3 observers. Use of more specific terms and detailed descriptions to categorize animals may help reduce such variability in observer scores.

The Manson and Leaver (1988) and Sprecher et al. (1997) systems assign discrete scores to animals. Another approach is to assess lameness on a continuous scale. For example, Welsh et al. (1993) found that a continuous scale for assessing lameness in sheep was more sensitive than a standard numerical rating system. Although more variation exists among continuous than discrete variables (e.g., Engel et al., 2003), using a continuous scale is probably more sensitive, allowing observers to record more subtle changes in behaviour. Both the continuous scale and the numerical rating system, however, are based on a simultaneous evaluation of multiple gait attributes. A new approach to lameness assessment, used in the current study, was to divide gait into specific gait attributes, scoring each attribute separately on a continuous scale, providing a more detailed profile of each cow's gait.

In the current study, we compared gait measures of lactating dairy cows with and without visible hoof pathologies, with the aim of evaluating 4 aspects of subjective gait assessments: a) validity of the methods (i.e., do they relate to hoof pathologies); b) reliability of assessments (i.e., how well correlated are observations within and among observers); c) whether continuous measures are better than numerical rating systems at predicting hoof pathologies; and d) whether specific gait attributes can be used alone or in combination to predict hoof pathologies.

3.2 Materials and methods

3.2.1 Cows and management

High-producing loose-housed Holstein dairy cows (n = 48) at the University of British Columbia's Dairy Education & Research Centre (Agassiz, Canada) were studied. Individual cows were selected randomly from the high-producing herd, with the constraint that 24 were primiparous and 24 were multiparous. Following hoof health assessment (see below), 8 cows with digital dermatitis were excluded and 2 were dropped for management reasons. The remaining primiparous (n = 18) and multiparous cows (parity = 2 to 7; n = 20) differed in BCS (3.1 ± 0.3 vs. 2.9 ± 0.3; $P < 0.05$) and daily milk production (28.7 ± 4.3 vs. 48.9 ± 6.3 kg; $P < 0.001$), but not DIM (96 ± 39 vs. 74 ± 37 d; NS).

Cows were milked twice daily in a parlour at 0500 and 1600 h, fed twice daily a TMR formulated to meet or exceed NRC (2001) requirements, and had free access to water in self-filling troughs. Stalls were deep-bedded with sand (0.40 m) and the flooring within 1.85 m of the feed bunk was grooved, 2.5 cm-thick rubber. Elsewhere in the pen, flooring was grooved concrete. Cows were cared for according to the standards of the Canadian Council on Animal Care and a protocol approved by the University of British Columbia's Animal Care Committee.

3.2.2 Data collection

Video recordings

To habituate cows to the filming conditions, cattle were walked to and from the milking parlour every day for 4 wk, along a 40-m grooved concrete test alley. A rope barrier in the test alley forced cows to walk in a straight line in single file with minimal side-to-side movement. The cows were allocated to 2 groups for management purposes. The first group of 24 cows was filmed after morning milking (between 0540 and 0810 h) for 7 consecutive days and then the procedure was repeated on the second group of 24 cows during the next 7 d. The test alley was cleaned with automatic scrapers at the beginning of each recording session.

A video camera (Panasonic AG-195MP, Matsushita Electric, Mississauga, Ontario) was fixed in position 6.75 m perpendicular to the line of progression of each cow. The camera captured cows walking the mid-section of the test alley (length 7.05 m, width 1.15 m) and recorded cows from the left side on return from the milking parlour. At least 2 consecutive strides were recorded per cow at every recording session.

Subjective assessment of gait

A trained observer (observer 1) scored video recordings using: a) a numerical rating system (**NRS**) with detailed descriptions; b) an overall visual analogue scale (**VAS**); and c) an evaluation of 6 specific gait attributes using a VAS. The NRS was based on a 5-point scale, in which a score of 1 represented a sound animal and 5 represented a severely lame animal (Table 3.1). If a cow exceeded the requirements of a particular score, but did not meet all the requirements of the next successive score, a half-integer score was allocated. A continuous 100-unit VAS was used to assess overall lameness (overall VAS) and 6 specific gait attributes associated with lameness (Table 3.2). Both ends of the scale had a description of the extreme forms of the condition. For example, degree of back arch had "flat" at one end (0) of the scale and "convex" at the other end (100), where "convex" represented the most extreme back arch the observer had seen in their experience. The observer recorded directly on a computer screen a position on the scale that represented the severity of the behaviour observed. Each video recording was observed 14 times: twice for each of the 6 gait attributes (in the order listed in Table 3.2), once for the overall VAS, and then once for the NRS. Of 336 video recordings, 25 were not scored because cows stopped, stumbled, slipped, defecated, urinated, or performed a gait other than walking. One recording was not scored because a cow walked too closely to another, potentially affecting the gait of both animals. To estimate intra-observer reliability, observer 1 re-scored recordings from 1 d selected at random, at least 7 d after the first scoring session, for each cow. To estimate inter-observer reliability, a second trained observer (observer 2) scored and re-scored this same sample of recordings. Both observers had at least 1 yr of experience in scoring gait using these techniques.

Clinical assessment of hooves

Injuries to the corium, the highly vascularized tissue responsible for producing hoof horn tissue, are not immediately visible on the surface of the sole. Damage to the corium results in haemorrhages, and in more severe cases, poor quality or no horn production (Ossent et al., 1997). Under normal conditions of hoof growth and wear, haemorrhages become visible approximately 8 to 10 wk after the occurrence of corium damage (Bergsten and Frank, 1996; Lischer and Ossent, 2000), but there is no reason to believe that the corium is still injured or painful at this stage. In cases in which corium damage is sufficiently severe that the sole becomes ulcerated, the injury may well continue to be painful even when fully visible at the surface of the sole. As we wished to understand how gait was affected by painful injuries, we recorded the presence of sole haemorrhages (**SH**) and sole ulcers (**SU**) after a professional hoof trimmer trimmed the front and hind hooves of each cow 8 to 9 wk after the gait assessment.

An experienced observer examined each hoof and recorded the presence of lesions using a modified version of a lesion scoring system (Greenough and Vermunt, 1991). Number, location, and severity of lesions on each hoof were scored on a 4-point scale [1 = slight discoloration, 2 = moderate hemorrhagic lesion, 3 = severe hemorrhagic lesion, 4 = sole ulcer (exposed corium)]. We also noted at this time the presence and location of digital dermatitis, both active (ulcerative or exudative lesions at the heel, with or without hair-like projections, painful to touch) and healed forms (dry, brown scabrous tissue, unresponsive to touch), as well as other foot pathologies such as interdigital hyperplasia and interdigital necrobacillosis.

Hoof health data of 2 cows were not collected because the cows were dropped from the trial due to coliform mastitis and early dry off for management reasons. Of the 46 cows examined, the majority had hoof pathologies (63%) at the time of examination. No cases of interdigital hyperplasia, interdigital necrobacillosis, or healed digital dermatitis were recorded; however, the presence of active digital dermatitis was noted on 8 cows. Because we could not be certain whether digital dermatitis was present at the time of video recording, these cows were dropped from the analysis. The remaining 38 cows were grouped into 3 mutually exclusive hoof health categories: a) healthy cows with no visible signs of injury or disease on hooves (n = 17); b) cows having only SH (n = 14); and c) SU cows having exposed corium and SH (n = 7).

3.2.3 Statistical analyses

Measures from each of the 7-d recordings were averaged to provide 1 value per cow. To test the effect of hoof health (2 df) on all dependent variables, we used contrast statements within the General Linear Model procedure of SAS (SAS Inst. Inc. Cary, NC) to test for specific predictions that: a) cows with SH (1 df) walked differently than healthy animals; and b) cows with SU (1 df) walked differently from healthy cows. Residuals were examined to verify normality and homogeneity of variances. The 6 behavioural gait attributes were also used in the Stepwise Discriminant Analysis procedure of SAS to determine which combination of specific gait measures could most accurately assign cows to hoof-health group. The criterion for entering or leaving the model was an alpha of 0.15. Correlation coefficients were calculated using the regression procedure (PROC REG) of SAS between a) first and second observations to test intra-observer reliability for observers 1 and 2, and b) between the mean values for the 2 observers to test inter-observer reliability.

3.3 Results

3.3.1 Validity

The walking gait profile of cows having SU differed from that of healthy animals (Table 3.3). Both the NRS and overall VAS assessments of lameness illustrated that cows having these pathologies had higher assessment scores than healthy animals. When walking behaviour was broken down into specific gait attributes, SU cows typically had more pronounced back arch, more jerky head movement, shorter strides, stiffer joint movements, more uneven hoof placement, and appeared more reluctant to bear weight evenly on all 4 limbs. The gait profiles of SH cows did not differ from those of healthy cows.

As older cows are more susceptible to injuries, we reanalyzed the data considering only multiparous cows. As with the analysis considering all cows, multiparous cows having SU (n = 6) differed ($P < 0.05$) from healthy cows (n = 5) in overall NRS and VAS as well as back arch, tracking-up, joint flexion, asymmetric gait, and reluctance to bear weight.

Given that cows with SU were different from healthy animals, stepwise discriminant analysis compared these 2 groups only. Overall VAS was effective in separating the 2 groups ($R^2 = 0.52$, $P < 0.001$; Figure 3.1a). Of all the measures recorded, however, the most effective at separating healthy cows from those having SU was NRS ($R^2 = 0.73$, $P < 0.001$; Figure 3.1b). Of the 6 gait attributes, the final stepwise model included only reluctance to bear weight. This model accounted for 51% of the variance in hoof health ($P < 0.001$; Figure 3.1c). Accuracy of classifying cows into healthy or SU groups by NRS, overall VAS, tracking-up, and reluctance to bear weight were very high at 92% (22 of 24 observations correctly classified by the model). Back arch, head bob and joint flexion were also accurate at 83%, and asymmetric gait was slightly lower at 75% (correctly classifying 18 of 24 observations).

3.3.2 Reliability

High intra-observer reliability was found for the NRS, overall VAS, head bob, and tracking-up variables (Table 3.4). Observer 1 also showed consistent scores for back arch, especially for more pronounced cases (Figure 3.2). Other variables, such as joint flexion and asymmetric gait, were scored less consistently by the same observer. Inter-observer reliability tended to be lower than intra-observer estimates, but the 2 observers were reasonably consistent in their estimates of some variables such as the overall VAS.

3.4 Discussion

Few studies have assessed the validity of subjective gait assessments to identify lame dairy cattle, and those that have report only weak relationships between hoof pathologies and gait scores. For example, Whay et al. (1997) reported that only 48% of variance in lesion severity was explained by an NRS. In the current study, we found that the NRS, overall VAS scores and the gait attributes tracking-up and reluctance to bear weight successfully distinguished cows having SU from healthy cows (with 22 of 24 cows correctly classified). The amount of variation explained by the NRS used in this study (73%) was much greater than reported in previous work, perhaps because the NRS used in the current study included detailed descriptions of each score. The NRS also provided a better estimate of hoof pathologies than the overall VAS, probably because the NRS used defined points. Other variation, not explained by the NRS, could result from other injuries not recorded. For example, we were unable to diagnose lameness caused by internal injuries or disease in the upper limb, because tools were not available to identify such conditions.

One of the unique contributions of this study is that we divided gait into separate attributes and found that scores for back arch, tracking-up, and reluctance to bear weight differed between SU and healthy cows. These results indicate that assessing specific gait attributes can be worthwhile. However, stepwise discriminant analysis was not able to form a combination of these variables that was any more successful at assigning cows to hoof health groups than the NRS. The SU cows had shorter strides and greater reluctance to bear weight when assessed subjectively. More objective methods of assessing these gait attributes might provide better discrimination between cows with and without hoof pathologies. For example, Flower et al. (2005) used kinematic measurements on the same sample of cows as described in the current study, and found that these objective measures were also able to discriminate between healthy cows and those with SU. In addition, Rajkondawar et al. (2002) successfully used measures of limb loading from force plates to identify lame dairy cows. Unfortunately, the technology required for these objective assessments is not readily accessible for many farms, meaning that subjective methods are still required for on-farm evaluations.

No significant differences were found in the gait of healthy cows and those having SH. The corium injuries leading to these haemorrhages may not be painful enough to alter gait, or grouping animals with minor, moderate and severe haemorrhages may have masked differences among groups. Indeed, Whay et al. (1997) suggested that mild lesions are probably not sufficiently painful to affect gait. Future studies should investigate the influence of haemorrhage severity on gait using a larger and more variable sample of cows with haemorrhages than was available in the current study.

Reasonable levels of intra-observer reliability were found for NRS, overall VAS, head bob, tracking-up, and back arch. Manson (1986) reported similar intra-observer reliability for her overall gait score of dairy cattle ($r = 0.89$), although these cows were observed from behind and scored live. Some specific gait attributes, like joint flexion and asymmetric gait, were scored less consistently in the current study, suggesting that these variables are more difficult to score. Consistency may be improved by using clearer definitions. For example, Garner et al. (2002) found that consistency improved when more detailed descriptions of broiler gait categories were provided. If consistency does not improve with better descriptions, however, these behaviours may need to be dropped from future studies. Intra-observer reliability obviously limits inter-observer reliability because different observers can be no more consistent than single observers are with themselves. Inter-observer reliability was still reasonable for some variables such as NRS, and this estimate ($r = 0.83$) agreed well with that of Manson (1986; $r = 0.84$).

Observers may vary in their assessments in part because cows vary in the way they walk. In this study, we controlled for some of this variation by scoring the same video recording. Previous studies that report reliability of gait scores usually present only the percentage agreement and not where the greatest variation of scores occurred (e.g., O'Callaghan et al., 2003). Our results suggest that intra-observer reliability for back arch (and other variables not illustrated) is greatest at the higher end of the scale, suggesting that cows with mild gait defects are more difficult to evaluate. Winckler and Willen (2001) reported similar results for inter-observer reliability, with most disagreement among observers at the lower end of the gait-scoring scale.

Typically, a delay of 8 to 10 wk exists between the time corium damage occurs and the time a haemorrhage or ulcer becomes visible on the sole of the hoof (Bradley et al., 1989; Bergsten and Frank, 1996; Lischer and Ossent, 2000). Based on these findings, hoof examinations in the current study occurred 8 to 9 wk after the end of the trial providing information on the presence of SH and SU. If we had scored hooves on the day of gait assessment, only haemorrhages that had formed 8 to 10 wk earlier (i.e., well before the gait assessment) would have been visible. Our choice of when to record lesions was based on the best evidence available regarding the time between injury to the corium and when signs of a lesion (i.e., haemorrhages and ulcers) become visible at the surface of the sole. Our aim was to assess the effects of these injuries to the corium on gait. A potential source of variation in this study, however, was the time course of more acute pathologies such as digital dermatitis. Future studies concerned with these factors may choose to use different hoof sampling frequencies.

Location of hoof pathology may affect which behavioural gait attributes are exhibited when cows walk. For example, back arch may only occur with pathologies located on the rear hooves. Unfortunately, in this study SU were only found on the hind hooves. Although we could not test for location of injury (e.g., front versus hind), future work should investigate how location of pathology affects cow gait.

Average gait scores were high in this study, even among apparently healthy cows. Little literature is available on average gait scores for healthy cows, and almost no results are available for high-producing cows in loose-housed systems with concrete flooring. The elevated gait scores observed in the current study, however, should not seem too surprising given how many cows have significant hoof pathologies. For example, Manske et al. (2002) found that 72% of cows investigated in Swedish herds had at least 1 hoof lesion. Similarly, Somers et al. (2003) surveyed herds in The Netherlands and found that 80% of the cows exposed to concrete flooring had at least 1 claw disorder at the time of observation. We suspect that the values reported in this study are not beyond the expected range for mid-lactation Holsteins housed in free-stall barns.

The elevated gait scores may also be explained by the walking surface. Previous work has shown that gait patterns change in response to the coefficient of friction of the flooring surface (Phillips and Morris, 2001; Telezhenko and Bergsten, 2005). Telezhenko and Bergsten (2005) also reported that cows walking on solid concrete floors had worse gait than on more yielding surfaces, such as rubber. For example, shorter stride lengths were observed on solid concrete versus rubber (1.48 ± 0.02 vs. 1.54 ± 0.02 m, respectively). Even though the alley was scraped before each recording in the current study, cows may have found the hard concrete surface slippery, or anticipated that it would be, resulting in higher scores.

In summary, the results from this study suggest that certain methods of gait assessment, such as the numerical rating system and overall visual analogue scales used, are both valid and reliable at identifying cows having SU. Other variables, such as joint flexion and asymmetric gait, showed limited reliability and are likely of little value when scored separately. Numerical rating systems were better at predicting SU than any other measures, and although most gait attributes were also able to predict such injuries, a combination of these variables was no more successful at identifying SU than the numerical rating system.

Table 3.1 Numerical rating system (NRS) for walking dairy cows.

NRS	Description	Behavioural criteria
1.0	Smooth and fluid movement	Flat back Steady head carriage Hind hooves land on or in front of fore-hooves (track-up) Joints flex freely Symmetrical gait All legs bear weight equally
2.0	Imperfect locomotion but ability to move freely not diminished	Flat or mildly arched back Steady head carriage Hind hooves do not track-up perfectly Joints slightly stiff Slightly asymmetric gait All legs bear weight equally
3.0	Capable of locomotion but ability to move freely is compromised	Arched back Steady head carriage Hind hooves do not track-up Joints show signs of stiffness Asymmetric gait Slight limp can be discerned
4.0	Ability to move freely is obviously diminished	Obvious arched back Head bobs slightly Hind hooves do not track-up Joints are stiff and strides are hesitant Asymmetric gait Reluctant to bear weight on at least one limb but still uses that limb in locomotion
5.0	Ability to move is severely restricted and must be vigorously encouraged to move	Extremely arched back Obvious head bob Poor tracking-up with short strides Obvious joint stiffness characterized by lack of joint flexion with very hesitant and deliberate strides Asymmetric gait Inability to bear weight on one or more limbs

Table 3.2 Description of 6 gait attributes associated with lameness[1].

	Endpoints of visual analogue scale	
Gait attribute	**0**	**100**
Back arch	Flat spine	Convex arch between the withers and tailbone
Head bob	Steady and even head carriage	Pronounced, uneven head movement
Tracking-up	Hind hoof falls in imprint left by the front hoof	Hind hoof falls short of imprint left by the front hoof
Joint flexion	Flexes and extends limbs through the normal range of motion	Limited flexion and extension resulting in stiffness
Asymmetric gait	Rhythmic 4-beat hoof placement	Arrhythmic hoof placement
Reluctance to bear weight	Bears weight equally over all legs	Uneven weight bearing among legs

[1]Scored on a 100-unit continuous visual analogue scale. A score of 0 represents a sound gait attribute and 100 represents the most extreme example the observer had seen in their experience.

Table 3.3 Least squares means (± SEM) of gait-scoring variables for healthy cows (n = 17), those having sole haemorrhages (n = 14), and those with sole ulcers (n = 7).

Variable	Hoof condition		
	Healthy	Sole haemorrhage	Sole ulcer
Numerical rating system (NRS)[1]	3.1 ± 0.08	3.3 ± 0.09	4.0 ± 0.13 ***
Overall visual analogue scale (VAS)[2]	46 ± 2	48 ± 2	59 ± 3 ***
Back arch[2]	12 ± 3	19 ± 3	28 ± 4 **
Head bob[2]	2 ± 2	5 ± 2	10 ± 3 *
Tracking-up[2]	7 ± 2	12 ± 3	26 ± 4 ***
Joint flexion[2]	21 ± 2	23 ± 2	32 ± 2 ***
Asymmetric gait[2]	18 ± 2	22 ± 2	27 ± 3 **
Reluctance to bear weight[2]	16 ± 2	19 ± 2	32 ± 3 ***

[1] Numerical rating system scored on a 5-point scale (see Table 3.1).

[2] Variables were scored on continuous 100-unit visual analogue scales (see Table 3.2)

*Different ($P < 0.05$) from healthy cows; **Different ($P < 0.01$) from healthy cows; ***Different ($P < 0.001$) from healthy cows.

Table 3.4 Correlation coefficients (r) for intra- and inter-observer reliability of gait-scoring variables (n = 46).

Variable	Intra-observer reliability: Observer 1	Intra-observer reliability: Observer 2	Inter-observer reliability
Numerical rating system (NRS)	0.87	0.92	0.83
Overall visual analogue scale (VAS)	0.91	0.87	0.85
Back arch	0.92	0.91	0.83
Head bob	0.91	0.88	0.85
Tracking-up	0.95	0.93	0.91
Joint flexion	0.75	0.75	0.62
Asymmetric gait	0.59	0.71	0.69
Reluctance to bear weight	0.80	0.85	0.83

Figure 3.1 Plot of a) overall visual analogue scale (VAS, •) measured using a 100-unit VAS, b) 5-pt numerical rating system (NRS, ○), and c) reluctance to bear weight (X) measured using a 100-unit VAS. Each plot shows healthy cows (H) (n = 17) and those with sole ulcers (SU) (n = 7).

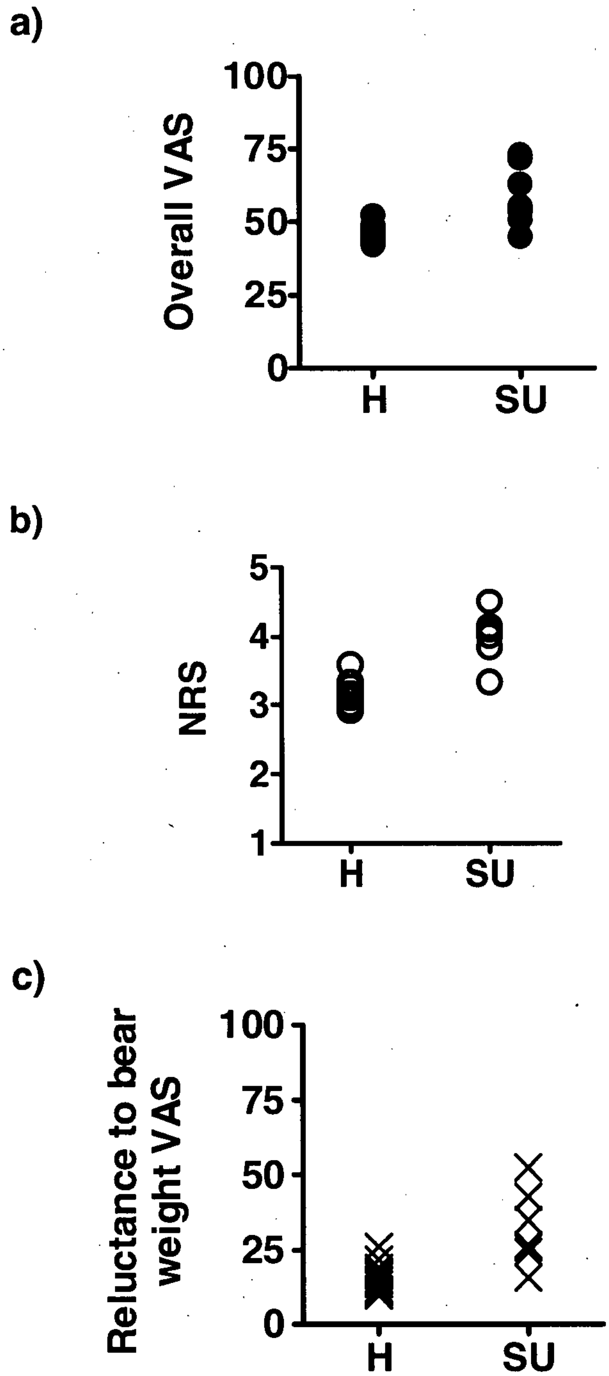
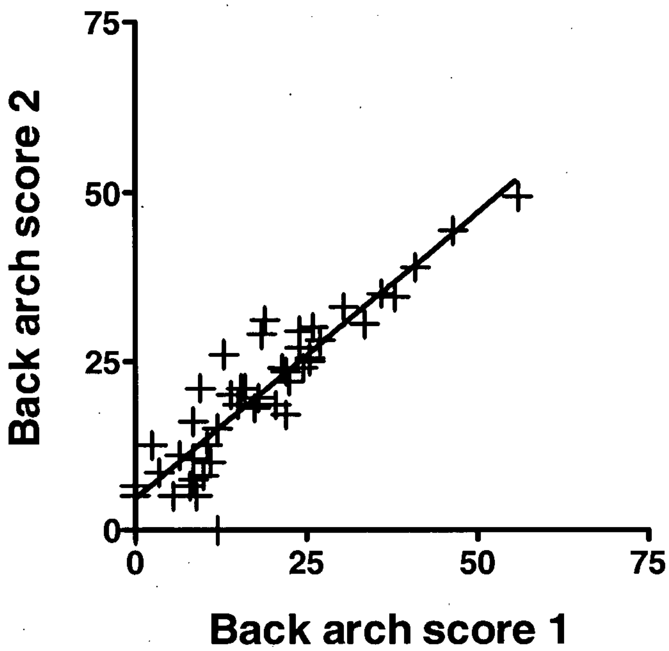


Figure 3.2 Intra-observer repeatability of observer 1 for back arch (r = 0.92; n = 46).



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CHAPTER 4: Effects of Milking on Dairy Cow Gait[3]

4.1 Introduction

With increases in the incidence of hoof and leg injuries and disease, research on dairy cattle lameness has grown considerably over the last 25 yr (Clarkson et al., 1996). Recent research has focused on improving methods of identifying sub-clinically lame cows (e.g., Flower et al., 2005), identifying which pathologies are painful (e.g., Whay et al., 1998), following the development of hoof pathologies over time (e.g., Webster, 2002), and understanding the risks factors for these pathologies (e.g., Bergsten, 2003).

Treating lameness, especially at the early stages, depends upon valid and reliable methods of identifying cows with hoof lesions. Recent studies have demonstrated that hoof pathologies can influence the way cows walk (e.g., Flower et al., 2005; Flower and Weary, 2006), but other factors may change gait, potentially affecting our ability to detect lame cows. For example, flooring features can alter gait: dairy cows have shorter strides on lower friction surfaces (Phillips and Morris, 2001), and longer strides on surfaces covered with manure slurry (Phillips and Morris, 2000).

Other cow features, such as physical conformation, may also affect gait. For example, Greenough et al. (1981) speculated that cows might swing their legs out while walking to avoid contact with a distended udder, although no research to date has tested how udder fill affects gait. Other studies on gait offer some insights. For example, horses prefer to trot at slower speeds when saddled with a heavy load (Wickler et al., 2001) and humans shorten their stride length when carrying extra weight (Martin and Nelson, 1986; Pascoe et al., 1997). Therefore it seems likely that cows with full heavy udders will change their gait. In addition, the effects of painful hoof injuries and disease may be more pronounced when cows are walking with a full

[3] A version of this chapter has been published. Flower, FC, DJ Sanderson, and DM Weary (2006) Effects of milking on dairy cow gait. J. Dairy Sci. 89: 2084-2089

udder compared with after milking. Understanding these effects may also provide a basis for recommending the most suitable times to conduct on-farm lameness assessments.

Traditionally changes in gait are assessed using subjective gait scoring methods (e.g., Manson and Leaver, 1988; Sprecher et al., 1997; Flower and Weary, 2006), but more recently researchers have begun using quantitative methods such as kinematic gait analysis and force platforms (Rajkondawar et al., 2002; Van der Tol et al., 2002; Flower et al., 2005). The aims of this experiment were to use both kinematic and subjective gait analysis to describe a) how cow gait changes after milking, and b) how these changes are affected by hoof pathologies, such as sole haemorrhages (**SH**) and sole ulcers (**SU**).

4.2 Materials and methods

4.2.1 Cows and management

High-producing Holstein dairy cows in loose-housing (n = 48) at the University of British Columbia's Dairy Education & Research Centre in Agassiz, Canada were studied. Individuals were randomly selected from the herd, with the constraint that 24 were primiparous and 24 were multiparous cows. After hoof health assessment (see below), 8 cows with digital dermatitis were excluded and 2 animals were dropped for management reasons. The remaining primiparous (n = 18) and multiparous cows (parity = 2 to 7; n = 20) differed in BCS (mean ± SD, 3.1 ± 0.3 vs. 2.9 ± 0.3; $P < 0.05$) and daily milk production (28.7 ± 4.3 vs. 48.9 ± 6.3 kg; $P < 0.001$), but not DIM (96 ± 39 vs. 74 ± 37 d).

Cows were fed a TMR diet twice a day, formulated to meet or exceed requirements for lactating dairy cows (NRC, 2001). Water was freely available from self-filling troughs. Stalls were deep bedded with 0.4 m of sand. Flooring within 1.85 m of the feed bunk was grooved 2.5 cm-thick rubber. Elsewhere in the pen, flooring was grooved concrete. Cows were milked in the parlour at 0500 h and 1600 h daily. Cows were cared for according to the standards of the Canadian Council on Animal Care and a protocol approved by the University of British Columbia's Animal Care Committee.

4.2.2 Data collection

To habituate cows to the filming conditions, animals were walked to and from the milking parlour daily for 4 wk, along a grooved concrete alley. A rope barrier in the alley forced cows to walk in a straight line in single file with minimal side-to-side movement. The cows were allocated to 2 groups for management purposes. The first group of 24 cows was filmed before and after morning milking (between 0510 h and 0810 h) for 7 d consecutively and then the procedure was repeated on the second group of 24 cows during the next 7 d. Data collected in the current study and by Flower et al. (2005) and Flower and Weary (2006) used the same cows, although the results reported in those earlier studies were only for cows walking from the parlour (i.e., after milking).

Kinematic gait analysis

Cows had a reflective marker, visible from all angles, wrapped around the entire circumference of each leg directly above the metacarpo- and metatarsophalangeal joints. The video recordings were digitized using PEAK Motus 7.1.1 (Peak Performance Technologies, Inc., Englewood, CO), and hoof-strike and toe-off events were defined visually from the video recordings by 1 observer. Hoof strike occurred when the hoof first contacted the ground at the beginning of the stance phase. Toe-off occurred when the toe left the ground at the end of the stance phase. Basic kinematic measures (stride length, maximum stride height, stride duration, stance and swing durations, and hoof speed) were then calculated for each hoof as defined in Table 4.1. The proportions of double support (time with 2 hooves in ground contact) and triple support (time with 3 hooves in ground contact) during the gait cycle were calculated from intervals between toe-off and subsequent hoof-strike and stride durations.

Subjective gait assessment

Using the same video recordings, a trained observer scored cow gait using a 1 to 5 numerical rating scoring system (**NRS**) (where 1 = sound and 5 = severely lame) outlined in detail in Flower et al. (2006), and an evaluation of 4 specific gait attributes (back arch, head bob, tracking-up, and reluctance to bear weight) using a 100-unit continuous scale. Both ends of the scale had a description of the extreme forms of the condition. For example, degree of back arch had "flat" at one end (0) of the scale and "convex" at the other end (100), where "convex" represented the most extreme back arch the observer had seen in their experience. The observer recorded directly on a computer screen a position on the scale that represented the severity of the behaviour observed. Each video recording was observed 9 times: twice for each of the 4 gait attributes, and once for the NRS.

Clinical assessment of hooves

Injuries to the corium, the highly vascularized tissue responsible for producing hoof horn tissue, are not immediately visible on the surface of the sole. Under normal conditions of hoof growth and wear, haemorrhages become visible approximately 8 to 10 wk after corium damage has occurred (Bergsten and Frank, 1996; Lischer and Ossent, 2000). As we wished to understand how gait was affected by painful injuries, we recorded the presence of SH and SU 8 to 9 wk after the trial. To do this, a professional hoof trimmer trimmed the front and hind hooves of each cow and an experienced observer examined each hoof and recorded the presence of lesions using a modified version of Greenough and Vermunt's (1991) lesion scoring system. Number, location and severity of lesions on each hoof were scored on a 4-point scale (1 = slight discoloration, 2 = moderate hemorrhagic lesion, 3 = severe hemorrhagic lesion, 4 = sole ulcer). At this time, we also noted the presence and location of digital dermatitis, both active (ulcerative or exudative lesions at the heel, with or without hair-like projections, painful to touch) and healed forms (dry, brown scabrous tissue, unresponsive to touch) and the presence of other foot pathologies, such as interdigital hyperplasia and interdigital necrobacillosis.

Hoof health data of 2 cows were not collected because the cows were dropped from the trial due to coliform mastitis and early dry off for management reasons. Of the 46 cows examined, the majority had hoof pathologies (63%) at the time of examination. No cases of interdigital hyperplasia, interdigital necrobacillosis or healed digital dermatitis were recorded; however, the presence of active digital dermatitis was noted on 8 animals. As we could not be certain whether digital dermatitis was present at the time of video recordings these animals were deleted from the analysis. Six additional cows were deleted as there were fewer than 2 d of suitable video recordings that could be digitized or scored due to missing markers or animals stopping, stumbling, slipping, defecating, urinating or performing any gait other than walking. The remaining 32 cows were grouped into 3 mutually exclusive hoof health categories: healthy cows with no visible signs of injury or disease on hooves (n = 15); cows having only SH (n = 11); and cows having SU and SH (n = 6).

4.2.3 Statistical analyses

We calculated mean kinematic stride variables using the first stride on the video recording per day by averaging across the 4 hooves and 7 d of video recordings for each cow for each direction (before and after milking). Subjective gait assessment variables from each of the 7 d of recording were averaged to provide 1 value per cow per direction.

Previously, Flower et al. (2005) and Flower and Weary (2006) found no differences between SH and healthy animals, therefore, we initially compared SH and healthy cows (1 df) using the General Linear Model procedure of SAS (SAS Inst. Inc. Cary, NC, 1985). For all variables, except reluctance to bear weight, no differences were found and therefore, SH and healthy cows were grouped as animals with no sole ulcers (**nSU**; n = 26). These variables were examined using the MIXED procedure of SAS to test the effect of hoof health (SU vs. nSU; 1 df), direction (before vs. after milking; 1 df), and the interaction between hoof health and direction (1 df), with cow as a random effect (30 df). For reluctance to bear weight, differences between the 3 hoof health groups were considered in an otherwise identical model. We ran the PROC REG procedure of SAS (30 df) separately for datasets before and after milking to describe the relationships with speed and among the various temporal kinematic variables.

4.3 Results

4.3.1 Kinematic gait analysis

On return to their home pen after milking, both nSU and SU cows had longer strides, higher stride height, shorter stride and stance durations, and walked faster than on their way to the milking parlour (Table 4.2). The proportion of triple support in the gait cycle dropped more than 6% after milking for both nSU and SU cows. Furthermore, cows with SU walked differently than cows without in all kinematic measures except for swing duration, both before and after milking: cows with SU walked with shorter strides, lower stride height, longer stride duration, longer stance duration, and walked more slowly than animals with nSU. An interaction between hoof health and milking was found for swing duration ($P < 0.05$). When SU and nSU cows were analyzed separately, animals with nSU had slightly longer swing durations before milking than after, but animals with SU showed no difference before and after milking.

The findings for speed and the temporal variables (stride, stance, and swing durations, and triple support) should not be considered independent. When cows walked faster (speed), the time taken to complete a stride (stride duration) decreased ($r = -0.90$). Stance duration ($r = 0.98$) and swing duration ($r = 0.80$) increased with increasing stride duration. A weaker, negative correlation was found between speed and proportion of triple support ($r = -0.55$), in other words as speed increased, less time was spent with 3 hooves in ground contact. Values reported are for data after milking, but very similar values were observed when analyzing the data from before milking.

4.3.2 Subjective gait assessment

Tracking-up improved after milking (Table 4.3), but no change was observed for NRS or back arch. Cows with SU had higher values for NRS, and walked with a more pronounced back arch and worse tracking-up compared with animals having nSU, both before and after milking. There was an interaction between hoof health and milking for head bob ($P < 0.05$); head bob slightly worsened for nSU cows, but improved for SU animals after milking. However, when nSU and SU groups were analyzed separately, the effect of milking was not significant.

The 3 hoof health groups differed in terms of reluctance to bear weight ($P < 0.001$, Figure 4.1). Cows with SU showed the greatest reluctance to bear weight when walking compared to healthy cows and cows with SH. This gait attribute improved after milking ($P <$

0.001), with the greatest improvement seen in cows with SU (mean ± SEM, 27 ± 2 vs. 19 ± 2). There was no evidence of an interaction between hoof health and milking.

4.4 Discussion

To our knowledge, this study is the first to demonstrate that dairy cow gait changes after milking. For example, nSU cows had longer strides (1.39 vs. 1.26 m) and shorter stride durations (1.30 vs. 1.42 s), resulting in a faster walk (1.08 vs. 0.89 m/s) after milking compared with before milking. These differences may be due to an increased motivation to walk after milking. All cows are likely to be motivated to return to their stalls and to fresh feed after milking, especially as cows tend to synchronize their feeding at this time (DeVries et al., 2003). Also, some cows may be fearful of the milking parlour (Rushen et al., 1999) and therefore reluctant to walk in that direction. There is evidence to suggest that motivation to feed can suppress pain caused by lameness when chickens are food-deprived (Wylie and Gentle, 1998). While cows in this study were not food-deprived, feeding motivation was likely high as both the availability and quality of feed improved after milking when fresh feed was provided, and this increased feeding motivation may have suppressed pain-related behaviours to some extent. This study was not specifically designed to test motivation to walk to the parlour or motivation to walk for food but future work is required to determine how motivation influences cow gait and the pain due to lameness.

Previous work on farm animals shows that differences in gait may result from differences in body conformation. For example, broiler chickens and turkeys, selected for large breast muscle and rapid growth rate, have a wider walking base and walk more slowly in comparison to birds with slower growth rates (Abourachid, 1991; Corr et al., 2003). Those studies concluded that gait differences resulted from a shift in the centre of gravity due to large breast muscle. Studies on conformation in cattle have focused on hoof conformation and its relationship to sole lesion development (Gitau et al., 1997; Offer et al., 2000), but little is known about other effects of body conformation in cattle. Only one study has examined how udder width and depth relate to subjective gait assessments, and found only weak correlations (r = 0.36; Boelling and Pollott, 1998).

Studies in other species can provide some insight into how gait may change when carrying a heavy load. For example, Wickler et al. (2001) measured speed in trotting horses saddled with an 85 kg weight versus no load and found that horses with a load prefer to trot at slower speeds. Moreover, humans carrying a heavy backpack have shorter stride lengths (Pascoe et al., 1997), longer double support times (2 feet in ground contact) and longer swing times (Martin and Nelson, 1986) than carrying no load. Findings in the current study were similar: slower speeds, shorter stride lengths, longer triple support times, and longer swing times when walking with a full udder (i.e., before milking). Daily milk production of cows in the current study averaged 38 kg/d, so milk weight represented approximately 3% of a cow's BW per milking. In contrast, the studies on horses and humans cited above used relatively greater weights (15 to 20% of the subject's BW) carried on the subject's back. Although the load experienced by the cows in the current study was smaller, the positioning of this load (in this case between the hind legs) may increase its effect. Time in triple versus double support was affected by walking speed; as observed in the current study, the faster a quadruped walks the less time spent in triple support. Thus, these differences in the ratio of triple support could also be due to cows walking more quickly when returning from milking. Indeed, all the kinematic variables are inter-related as they are all aspects of how each cow walks. Herlin and Drevemo (1997) were the first to report a negative correlation between speed and stride duration (r = -0.55), and a positive correlation between stride and stance duration (r = 0.56). We found similar but stronger relationships between these measures.

Stance durations of cows in this study were on average 0.16 s longer and swing durations 0.13 s shorter than reported by Flower et al. (2005), resulting in an increase in time spent in triple support. The differences are likely due to differences in the way that stance and swing durations were calculated; toe-off (when the toe leaves the ground) was used to define the end of the stance phase in the current study, versus hoof-off (when the hoof first leaves the ground) in Flower et al. (2005).

Previous research has shown that cows with SU walk differently from healthy animals (Flower et al. 2005; Flower and Weary, 2006). The current study supports those findings; based on the NRS values, animals with SU had lower gait scores than cows with nSU. Furthermore, cows with SU had shorter strides, longer stride durations, walked more slowly, had a pronounced back arch and worse tracking-up compared with animals having nSU. Although there was no interaction between milking and hoof health, differences before and after milking were greater numerically for cows with nSU than for cows with SU. Animals with SU were likely to have adjusted their gait to minimize pain experienced during loading of the affected limb, and may have been less able to adjust their gait further in response to the extra weight from the milk and udder distension.

In conclusion, both the effect of milking and the effect of painful sole ulcers change the gait pattern of cows. While most of the gait attributes did not show clear differences before and after milking, all the kinematic measures demonstrated a clear improvement and greater numerical difference between nSU and SU cows after milking. These results suggest that the most suitable time to conduct on-farm lameness assessments of dairy cattle is after milking.

Table 4.1 Description of stride variables calculated from kinematic measurements.

Variables	Description
Spatial	
Stride length, cm	Horizontal displacement between 2 consecutive hoof strikes of the same hoof
Maximum stride height, cm	Maximum vertical displacement between 2 consecutive hoof strikes of the same hoof
Temporal	
Stride duration, s	Time interval between 2 consecutive hoof strikes of the same hoof
Stance duration, s	Time the hoof is in contact with the ground (interval between hoof strike and following toe-off)
Swing duration, s	Time the hoof is not in contact with the ground (interval between toe-off and following hoof strike)
Hoof speed, m/s	Stride length/stride duration

Table 4.2 Least squares means ± SEM of basic kinematic stride variables before and after milking for cows with no sole ulcers (nSU; n = 26) and cows with sole ulcers (SU; n = 6).

	nSU		SU		P[1]		
Variable	**Before**	**After**	**Before**	**After**	**M**	**H**	**M*H**
Stride length, cm	126.3 ± 1.7	139.1 ± 1.7	120.5 ± 3.6	127.8 ± 3.6	<0.001	<0.05	NS
Stride height, cm	8.6 ± 0.2	9.5 ± 0.2	7.9 ± 0.3	8.2 ± 0.3	<0.01	<0.01	NS
Stride duration, s	1.42 ± 0.03	1.30 ± 0.03	1.55 ± 0.06	1.52 ± 0.06	<0.01	<0.01	NS
Stance duration, s	0.97 ± 0.02	0.86 ± 0.02	1.12 ± 0.05	1.07 ± 0.05	<0.001	<0.01	NS
Swing duration, s	0.45 ± 0.01	0.44 ± 0.01	0.43 ± 0.01	0.45 ± 0.01	NS	NS	<0.05
Speed, m/s	0.89 ± 0.02	1.08 ± 0.02	0.80 ± 0.05	0.87 ± 0.05	<0.001	<0.01	NS
Triple support, %	72.5 ± 1.7	65.9 ± 1.7	87.5 ± 3.6	77.4 ± 3.6	<0.001	<0.001	NS

[1] P-values for the effects of milking (**M**: before vs. after milking), hoof health (**H**: nSU vs. SU), and their interaction (**MxH**).

Table 4.3 Least squares means ± SEM of subjective gait assessment before and after milking for cows with no sole ulcers (nSU; n = 26) and cows with sole ulcers (SU; n = 6).

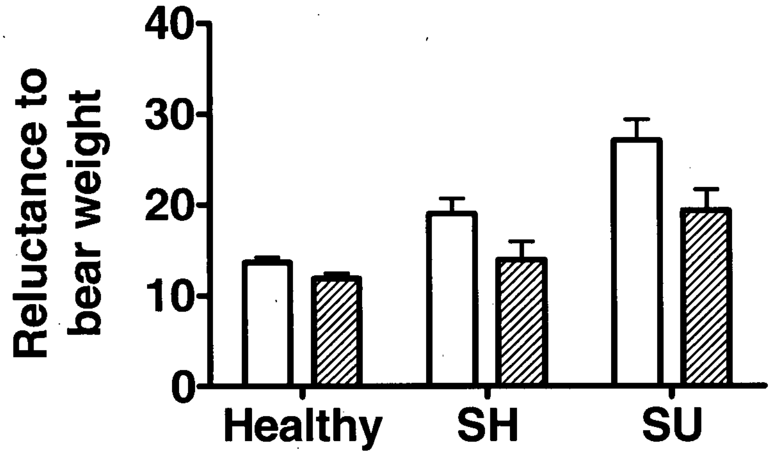
	nSU		SU		P^3		
Variable	**Before**	**After**	**Before**	**After**	**M**	**H**	**M*H**
Numerical rating system[1]	3.4 ± 0.1	3.2 ± 0.1	3.8 ± 0.1	3.8 ± 0.1	NS	<0.01	NS
Back arch[2]	22 ± 2	23 ± 2	39 ± 5	37 ± 5	NS	<0.01	NS
Head bob[2]	2 ± 1	3 ± 1	6 ± 2	3 ± 2	NS	NS	<0.05
Tracking up[2]	14 ± 2	8 ± 2	26 ± 4	24 ± 4	<0.01	<0.01	NS

[1]Numerical rating system scored on a 5-point scale.

[2]Variables were scored on continuous 100-unit visual analogue scales. Both ends of the scale had a description of the extreme forms of the condition. For example, degree of back arch had "flat" at one end (0) of the scale and "convex" at the other end (100), where "convex" represented the most extreme back arch the observer had seen in their experience.

[3]*P*-values for the effects of milking (**M**: before vs. after milking), hoof health (**H**: nSU vs. SU), and their interaction (**MxH**).

Figure 4.1 Least squares means ± SEM of reluctance to bear weight, scored using a 100-unit continuous scale, are shown for healthy cows (n = 15), cows with sole haemorrhages (SH; n = 11) and cows with sole ulcers (SU; n = 6) before (empty bars) and after (shaded bars) milking.



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CHAPTER 5: Softer, Higher-Friction Flooring Improves Gait of Cows With and Without Sole Ulcers[4]

5.1 Introduction

Concrete flooring is widely used in dairy barns due to its low cost, durability and ease of cleaning; however, concrete surfaces are a risk factor for the development of hoof pathologies, including sole and white line haemorrhages, sole ulcers, digital dermatitis, and heel horn erosion (Wells et al., 1999; Vokey et al., 2001; Somers et al., 2005). Hoof injuries and disease are a concern for dairy producers because of the large numbers of cows affected (Clarkson et al., 1996; Cook, 2003; Whitaker et al., 2004), and because such injuries can cause pain, reduce feed intake (O'Callaghan, 2002) and milk production (Green et al., 2002), and increase reproductive problems (Hernandez et al., 2005).

Recent research has shown that flooring surfaces that have higher surface friction or are softer can improve some measures of cow mobility. For example, cows had longer strides and more joint angulation on high- versus low-friction concrete (Phillips and Morris, 2001) and cows walked faster and slipped less on soft, high-friction rubber versus lower-friction concrete floors (Rushen and de Passillé, 2006).

Little research has investigated the effects on gait of softer, more yielding flooring, especially for cows with painful hoof injuries and disease. Telezhenko and Bergsten (2005) reported that rubber mats improved gait (increased stride length and decreased step asymmetry) for both lame and non-lame cows compared with 4 other flooring surfaces, including solid concrete; however the effects of flooring were confounded by the order of flooring exposure. Although alternatives to concrete flooring would appear to be beneficial for lame cows, this has not been tested systematically. Understanding these effects will provide a basis for recommending more suitable flooring, particularly for cows with hoof pathologies.

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Kinematic gait analysis and subjective gait assessments have both been used to characterize the gait of cows and distinguish cows with sole ulcers from healthy ones (Flower et al., 2005; Flower and Weary, 2006). The aim of the current study was to use both techniques to compare cow gait on concrete flooring and a composite rubber surface, and to determine how these changes are affected by hoof pathologies.

5.2 Materials and methods

5.2.1 Cows and management

We studied 30 Holstein dairy cows (parity 1 to 8, mean ± SD BM 641 ± 75 kg) of which 28 were lactating (DIM 164 ± 68 d, milk production 26.8 ± 6.1 kg/d) and 2 were non-lactating, from the herd at the Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, Lennoxville, Quebec, Canada. All cows were housed in tie-stalls on rubber-filled geotextile mattresses with a covering of chopped straw. Cows were milked in the parlour at 0700 h and 1900 h daily, fed a TMR formulated to meet or exceed NRC (2001) requirements supplied ad libitum, and had free access to water in self-filling troughs.

5.2.2 Data collection

Video recordings

Cows were filmed walking along 1 of 2 identical 1.1 x 22.4 m corridors (see Rushen and de Passillé, 2006). A rope barrier between the 2 corridors forced cows to walk in a straight line with minimal side-to-side movement. During a habituation phase, the cows were trained to walk through each corridor over 2 days and at the end of each corridor a food reward (a mixture of grain and hay) was offered.

The floor of each corridor was covered with 1 of 2 flooring surfaces: un-grooved concrete and a composite rubber surface comprising Animat® as the bottom layer (1.9 cm thick, Animat Inc., Saint-Élie d'Orford, QC, Canada), a middle layer of felt (1.5 cm thick polypropylene / polyester mix), and a top surface of high-friction slip-resistant rubber (0.6 cm thick, #125 2ply Cobelt Canada Inc., Saint-Laurent, QC, Canada). The total thickness of the composite rubber surface was 4.0 cm. The types of material are described in more detail by Rushen and de Passillé (2006) who report that static and dynamic coefficients of friction and degree of compressibility were substantially higher on the composite rubber surface than on concrete.

We examined the gait of cows walking on both surfaces on both corridors using a balanced design within cow. Cows were randomly allocated to 2 groups and tested over 2 d. Group 1 (n = 16) was filmed on the first day with the composite rubber surface in corridor 1 and concrete in corridor 2 and on the second day the surfaces were switched. Group 2 (n = 14) was filmed on the first day with the composite rubber surface in corridor 2 and concrete in corridor 1 and on the second day the surfaces were switched. Each cow was tested alternately on each surface with the order of exposure to the flooring surfaces balanced across cows. All testing was performed between 0900 and 1400 h. To minimise the occurrence of slipping, corridors were cleaned manually at the beginning of each test.

Two video cameras were fixed in position 9.6 m from the corridors and perpendicular to the direction of movement of the cows. One camera captured kinematic data (Panasonic AG-456UP, Matsushita Electric, Mississauga, ON, Canada) and one captured data used for gait scoring (Sony Video8 Handycam Camcorder CCD-FX730V, Sony Corporation, Park Ridge, NJ, USA). Both cameras filmed the cows from the right side while they were walking in the mid-section of the alley (length 7.4 m). To supply adequate light, a 500W helium floodlight was attached above the cameras and directed at the corridors. Three 100W light bulbs were placed in the ceiling above the alley as an additional lighting source. Cameras (Panasonic WP-310, Matsushita Electric, Mississauga, ON, Canada) were also positioned above the corridors to obtain a posterior view of cows as they walked. At every recording session at least 2 consecutive strides were recorded per cow.

On both test days, cows were walked (for a food reward) at least 3 times per corridor per day, although only the last 2 passages of each corridor per day were assessed. Thus, for each cow, 4 passages on each surface were scored over the test days. Of the 240 passages scored, 10 were not used because cows tripped, slipped, stopped, jumped, trotted or ran.

Kinematic gait analysis

Cows were fitted with reflective markers, one on each leg, which were visible from all angles, and wrapped around the entire circumference of each leg directly above the metacarpo- and metatarsophalangeal joints at least 1 h before filming (see Flower et al., 2005). The video recordings were digitized using PEAK Motus 7.1.1 (Peak Performance Technologies, Inc., Englewood, CO, USA), and hoof strike and toe-off events were defined visually from the video recordings by 1 observer. Hoof strike occurred when the hoof first contacted the ground at the beginning of the stance phase. Toe-off occurred when the toe left the ground at the end of the stance phase. Basic kinematic measures (stride length, maximum stride height, stride duration, stance and swing durations, and hoof speed) as well as triple support and stride overlap were then calculated according to the criteria given in Table 5.1.

Subjective gait assessment

Using the video recordings, an experienced observer scored each cow's gait, from both posterior and lateral views, on a numerical rating system (**NRS**) from 1 to 5, where 1 = sound and 5 = severely lame (Flower and Weary, 2006). Previous scoring systems classified cows with scores of 3 and higher as lame (e.g., Manson and Leaver, 1988; Whay et al., 1997), however, in this study we treated lameness (measured as NRS) as a continuum. In addition, 6 specific gait attributes (back arch, head bob, tracking-up, joint flexion, asymmetric gait, and reluctance to bear weight) were scored using 100-unit continuous visual analogue scales (defined in Flower and Weary, 2006). A seventh behaviour was also scored using a visual analogue scale: abduction/adduction was assessed from a posterior view and was defined as swinging the hind limbs either away from (abduction) or towards (adduction) the body in a circular motion during the swing phase of the stride. The ends of the visual analogue scale had a description of the extreme forms of the condition. For example, degree of back arch was defined as "flat" at one end (0) of the scale and "convex" at the other end (100), where "convex" represented the most extreme back arch the observer had seen in their experience. The observer recorded directly on a computer screen a position on the scale that represented the severity of the attribute. Each video recording was observed 9 times: twice for NRS, once for back arch and head bob, once for tracking-up, once for joint flexion, once for asymmetric gait, once for reluctance to bear weight, and twice for abduction/adduction. The observer assessed gait of all cows for 1 passage before scoring the next passage. To test intra-observer consistency, a sub-sample of 13 cows were re-scored by the same observer at the end of the study.

Clinical assessment of hooves

Hooves were examined twice after data collection. On the first assessment, which occurred immediately after the trial, a trained observer examined each cow for the presence of digital dermatitis, interdigital hyperplasia, and interdigital necrobacillosis, but no cases were found. Based on previous literature, which showed that sole haemorrhages became visible 8 to 10 wk after corium damage occurred (Bergsten and Frank, 1996; Lischer and Ossent, 2000), the second hoof assessment occurred 9 wk after the trial. A professional hoof trimmer trimmed and examined the front and hind hooves of cows and recorded the presence of sole and white line haemorrhages, sole ulcers (**SU**), and heel erosion using Neveux et al.'s (2006) scoring system (Table 5.2). Cows with hoof pathologies were treated at the end of the trial.

Of the 30 cows assessed, the majority (76%) had 1 or more hoof pathology at the time of the second hoof examination. Cows were grouped into 3 mutually exclusive categories based on hoof health: healthy cows with no visible signs of injury or disease on hooves (n = 7); cows having only sole and white line haemorrhages (n = 13); and cows with SU plus sole and white line haemorrhages (n = 10).

Morphometric Measures

To ensure that differences in gait between these cows was not an effect of any differences in body size, the mean body mass of each cow was recorded once and height at the withers (T3), height at the tailbone (Cc1) and the length of the back (T3-Cc1) were measured 3 times from the left side. Measurements were only taken when cows were standing with the head raised and legs straight. No differences ($P > 0.10$) were detected among groups for any of these measures: mean body mass (± SD) was 641 ± 75 kg, height at the withers was 143 ± 3 cm, height at the tailbone was 146 ± 3 cm, and length of back was 126 ± 6 cm.

5.2.3 Statistical analyses

We calculated mean kinematic stride variables using the first stride on the video recording per passage and averaging across the 4 hooves and 2 d of video recordings, to provide 1 value per cow for each surface. Subjective gait assessment variables were also averaged across days to provide 1 value per cow per surface.

Previously, Flower et al. (2005) and Flower and Weary (2006) found no differences in any gait measures between cows with sole haemorrhages and healthy animals; therefore, we initially compared cows with sole and white line haemorrhages versus healthy cows (1 df) using the General Linear Model procedure of SAS (SAS Inst. Inc. Cary, NC, 1985). Again, no differences ($P > 0.10$) were found so these cows were grouped together as animals with no sole ulcers (**nSU**) (n = 20). Variables were then tested using the MIXED procedure of SAS, specifying cow as a random effect. The effects of hoof health (i.e., SU vs. nSU; 1 df), surface (i.e., concrete vs. rubber; 1 df), and the interaction between hoof health and surface (1 df) were tested against an error term with 28 df.

We also tested if cows with higher gait scores (i.e., lame cows) showed a greater response to the flooring treatment than cows with lower scores. We calculated the difference between the 2 surfaces (concrete minus rubber) for each variable for each cow and regressed this difference against the cow's average gait score on concrete using the PROC REG procedure of SAS, tested against an error term with 28 df.

To test intra-observer reliability of the subjective gait variables, correlation coefficients were calculated using the PROC REG procedure of SAS between first and second observations of a sub-sample of cows (n = 13).

We used the PROC DISCRIM procedure of SAS to test how accurately each gait attribute, and the overall assessment of gait used in this study (NRS), correctly classified cows with SU from those without.

Lastly, stride overlap and tracking-up recorded the degree of front and rear hoof overlap in different 2 ways: stride overlap was measured using kinematics and tracking-up was assessed subjectively. As tracking-up only assessed shortness of stride (assigning a score of 0 regardless of whether the rear hoof landed on or in front of the front hoof) and stride overlap measured both underlap and overlap, the Pearson correlation coefficient with tracking-up was calculated on the underlap data only.

5.3 Results

5.3.1 Kinematic gait analysis

Flooring type affected a number of kinematic variables. Cows had longer stride lengths, higher maximum stride height, more overlapping, spent less time in triple support during the gait cycle (i.e., 3 hooves in ground contact), and walked faster on the composite rubber surface than on concrete (Table 5.3). However, stride duration and stance duration were not affected by flooring. Furthermore, no differences were found between cows with and without SU for any kinematic stride variables except stride height; cows with SU had lower stride height than cows without.

An interaction between hoof health and flooring surface was found for swing duration: SU cows had longer swing durations on the composite rubber surface compared with concrete but nSU cows showed no difference between the 2 surfaces. There was also a trend for an interaction between hoof health and surface for stride overlap; with the effect of rubber greater for SU cows.

For several variables, cows with higher gait scores (i.e., more severe lameness) showed the greatest response to the composite rubber surface (Figure 5.1). The correlations between gait score (tested on concrete) and differences between concrete and the composite rubber surface were greatest for stride length ($r = -0.51$, $P < 0.01$), swing duration ($r = -0.44$, $P < 0.05$), triple support ($r = 0.59$, $P < 0.001$), and stride overlap ($r = -0.50$, $P < 0.01$). However, the relationship between gait score and stride overlap (see Figure 5.1c) appeared to be driven by one cow. Reanalysis excluding this cow found a non-significant relationship ($r < 0.10$, NS). The correlations were not significant for stride height, stride and stance duration, and speed ($r < 0.18$, NS).

5.3.2 Subjective gait assessment

Overall, cow gait improved when cows walked on the composite rubber surface: NRS, tracking-up, joint flexion, asymmetric gait, reluctance to bear weight, and abduction/adduction all decreased on the rubber flooring (Table 5.4). Cows with SU had higher values for NRS, poorer tracking-up, worse joint flexion, more asymmetric gait and showed more reluctance to bear weight compared with nSU cows, both on rubber and concrete flooring. No interactions between hoof health and surface were observed for any subjective gait variables.

Cows with the highest gait scores showed the greatest improvement in NRS ($r = 0.46$, $P < 0.01$) and in reluctance to bear weight ($r = 0.66$, $P < 0.001$) when walking on the composite rubber surface compared to concrete (Figure 5.2). Relationships were weaker for tracking-up ($r = 0.44$, $P < 0.05$), joint flexion ($r = 0.36$, $P < 0.05$), and asymmetric gait ($r = 0.40$, $P < 0.05$) and were not significant for back arch, head bob or abduction/adduction ($r < 0.34$, NS).

Intra-observer scoring consistency was high for NRS ($r = 0.97$, $P < 0.001$), back arch ($r = 0.92$, $P < 0.001$), head bob ($r = 0.84$, $P < 0.001$), tracking-up ($r = 0.96$, $P < 0.001$), joint flexion ($r = 0.91$, $P < 0.001$), asymmetric gait ($r = 0.90$, $P < 0.001$), and reluctance to bear weight ($r = 0.96$, $P < 0.001$). Only moderate consistency was found for abduction/adduction ($r = 0.68$, $P < 0.01$).

The accuracy of classifying cows into those with or without SU was high when based on NRS (71%; 12 of 17 observations correctly classified by the model). Of all the other subjective measures, asymmetric gait correctly classified most cows (76%; 13 of 17 observations). Back arch, tracking-up and reluctance to bear weight were less accurate (59%) and head bob and joint flexion correctly classified 47% and 53% of cows, respectively.

As expected, the subjective and objective assessments of overlap (i.e., stride overlap and tracking-up) were negatively correlated for cows walking on concrete ($r = -0.50$) Therefore, cows with poor tracking-up (high positive value) would also have a large underlap (high negative value).

5.4 Discussion

In this study, dairy cow gait profiles were influenced by flooring surface. Kinematic measures of gait were strongly affected by the surface that cows were walking on. Specifically, cows had longer and higher strides, more overlapping, longer swing durations, spent less time in triple support, and walked faster when walking on the composite rubber surface compared to walking on concrete. The overall gait score (NRS) was also lower and subjective scoring showed that cows had greater tracking-up, improved joint flexion, more symmetric gait, were able to bear weight more evenly over all legs, and displayed less abduction/adduction on the composite rubber surface. These findings correspond to those reported by Telezhenko and Bergsten (2005) who found that cows had better overall gait scores (assessed using a modified version of Sprecher et al.'s (1997) system), walked faster, had longer strides, and more overlapping on rubber than concrete. However, the effects of flooring reported by Telezhenko and Bergsten (2005) were confounded by order of exposure to flooring surface. In addition, Telezhenko and Bergsten (2005) walked cows through a mixture of slurry and lime so that hoof imprints could be measured, but this recording method may have altered the degree of friction between the hoof and flooring and potentially affected gait.

The faster speed, more overlapping, lower proportion of triple support, and less reluctance to bear weight suggest that cows had better footing on the softer, high-friction composite rubber surface than concrete. Indeed, Rushen and de Passillé (2006) reported a lower incidence of slipping when cows were walking on similar flooring. As hooves were able to sink into the rubber flooring, more contact was created between hooves and the flooring surface. The composite rubber surface also had a higher frictional coefficient than concrete (see Rushen and de Passillé, 2006), which likely added to a more secure footing. These results support earlier work that showed cows adjusted their manner of walking in response to surface softness and friction: Phillips and Morris (2001) reported that cows had longer strides and more joint angulation on high- versus low-friction concrete.

The composite rubber surface also provided more cushioning than concrete, and this cushioning has also been shown to improve cow mobility (Rushen and de Passillé, 2006). In human studies, Lafortune and Hennig (1992) reported that providing more cushioning (i.e., wearing athletic shoes compared with walking barefoot) reduced the peak forces experienced at impact and reduced the rate of loading when walking on concrete. In the current study, the composite rubber surface also likely reduced the rate of limb loading. Future work needs to examine quantitative assessments of weight-bearing during walking especially in relation to surfaces with differing compressibility.

Some gait measures were not affected by the softer, higher-friction composite rubber surface (i.e., stride duration, stance duration, back arch and head bob). Indeed, some of these gait features may be generally unresponsive to treatment differences. For example, recent work has indicated that swing duration, back arch and head bob were not able to detect differences in cow gait before and after milking (Flower et al., 2006).

Most of the subjective gait variables distinguished between cows with and without SU, replicating recent work by Flower and Weary (2006). However, unlike Flower et al. (2005), kinematic variables in the current study did not distinguish between cows with and without SU. Gait measures, in general, showed weaker relationships with hoof health in the current study compared to the findings reported in Flower et al. (2005) and Flower and Weary (2006). As the gait measures in all 3 studies were recorded and analysed in the same way, differences in housing and in the assessment of hoof health may explain these weaker relationships. Firstly, the standing and walking surfaces for cows in Flower et al.'s (2005) study were more abrasive (cows were loose-housed in concrete pens with deep-bedded sand stalls versus cows housed in tie-stalls on rubber mattresses) and probably resulted in a faster rate of hoof wear than in the current study, reducing the time required for haemorrhages to become visible on the surface of the sole. This difference may have meant that the delay between gait and hoof scoring that was suitable in the first study was no longer suitable in the current study, reducing our ability to detect differences in gait associated with SU. Secondly, although the same observer analysed gait in both studies, hoof examinations were conducted by different observers, using different lesion scoring systems.

This study compared an objective measure of overlap (stride overlap) with the subjective measure (tracking-up), and to our knowledge, this is the first study to directly compare the 2 approaches. Although these variables were related, variation in stride overlap only accounted for 26% of the variance in the subjectively assessed tracking-up. This lack of fit may have been because the 2 variables recorded different aspects of overlap: stride overlap was based on an average of the left and right sides, whereas tracking-up assessed both left and right sides but assigned a score based on the worst side. Although both measures were equally effective at distinguishing the effect of flooring surface, the subjective measure was more successful at identifying cows with SU. This last result suggests that the subjective measure captured some (as yet unidentified) aspect of gait impairment not included in the kinematic measure stride overlap.

Gait measures for cows walking on concrete were similar to those reported by Flower et al. (2005) and Flower and Weary (2006), although some measures, such as stride length, NRS, and back arch were lower in the current study, perhaps due to differences between herds and housing systems. The gait measures also demonstrated that relying on a single behavioural attribute to identify cows with SU, as in Sprecher et al.'s (1997) study, could be misleading as several cows in the current study would be misclassified using just back arch. Indeed, the stepwise discriminant analysis was not able to form a combination of gait measures that was any more successful at assigning cows to hoof health groups than NRS. Furthermore, the intra-observer consistency in scoring of most subjective gait variables was similar or better than that reported by Flower and Weary (2006), although the moderate consistency for the abduction/adduction suggests that this attribute is more difficult to score and therefore of limited value.

An important finding of this study was that for a number of gait variables (both kinematic and subjective) gait score affected how cows responded to the flooring surface. Changes in triple support, stride overlapping, NRS, and reluctance to bear weight were positively correlated with gait score, and stride length and swing duration were negatively correlated with gait score. These results suggest that cows with high gait scores benefit the most from a softer, higher-friction surface. Further work is needed to investigate which properties of the composite rubber flooring are most important for cow gait. Some work is emerging on surface friction (Phillips and Morris, 2001) and softness (Rushen and de Passillé, 2006) but to date, the effects of different flooring properties on lame cows have not been investigated.

In conclusion, most measures demonstrated a clear improvement in gait when cows walked on the composite rubber surface versus concrete flooring. This suggests that rubber flooring provided more secure footing and was more comfortable for cows to walk on. Lame cattle, in particular, showed the greatest improvement, suggesting that lame cows may especially benefit from more comfortable flooring and that gait assessment methods should account for flooring surface in any future analysis of dairy cow gait.

Table 5.1 Description of the kinematic stride variables.

Variable	Description
Spatial	
Stride length, cm	Horizontal displacement between 2 consecutive hoof strikes of the same hoof
Maximum stride height, cm	Maximum vertical displacement between 2 consecutive hoof strikes of the same hoof
Stride overlap, cm	Horizontal distance between front hoof strike and subsequent ipsilateral rear hoof strike. A positive value indicates that the rear hoof lands in front of the front hoof and a negative value indicates that the rear hoof lands short of the front hoof.
Temporal	
Stride duration, s	Time interval between 2 consecutive hoof strikes of the same hoof
Stance duration, s	Time the hoof is in contact with the ground (interval between hoof strike and following toe-off)
Swing duration, s	Time the hoof is not in contact with the ground (interval between toe-off and following hoof strike)
Speed, m/s	Stride length/stride duration
Triple support, %	(Sum of intervals between toe-off and subsequent contralateral hoof strike/ stride duration) * 100

Table 5.2 Description of hoof health scoring system (from Neveux et al., 2006).

Pathology	Severity Score	Description
Dermatitis	1	Light dermatitis
	2	Moderate dermatitis
	3	Severe dermatitis, dermis is exposed
Heel erosion	1	Light heel erosion
	2	Moderate heel erosion
	3	Severe heel erosion, dermis is exposed
Sole/white line haemorrhage	1	Light haemorrhage, petechia or localized haemorrhage with altered coloration covering less than 10% of the sole or white line
	2	Moderate haemorrhage covering 10-25% of the sole or white line
	3	Severe haemorrhage covering more than 25% of the sole or the white line, or deep red haemorrhage in a localized region
Sole ulcer	1	Insult to sole exposing dermis
	2	Insult to sole with exposed corium
	3	Insult to sole with exposed corium and signs of infection

Table 5.3 Least squares means ± SEM of basic kinematic stride variables on concrete and a composite rubber surface, for cows with no sole ulcers (nSU; n = 20) and cows with sole ulcers (SU; n = 10).

	nSU		**SU**		***P*[1]**		
Variable	**Concrete**	**Rubber**	**Concrete**	**Rubber**	**S**	**H**	**S*H**
Stride length, cm	152.2 ± 1.8	156.9 ± 1.8	149.6 ± 2.6	156.9 ± 2.6	0.001	>0.10	>0.10
Stride height, cm	9.6 ± 0.2	10.6 ± 0.2	8.8 ± 0.3	9.7 ± 0.3	0.001	0.019	>0.10
Stride overlap, cm	0.9 ± 1.4	3.7 ± 1.4	-4.3 ± 2.0	0.4 ± 2.0	0.001	0.089	0.058
Stride duration, s	1.28 ± 0.02	1.27 ± 0.02	1.29 ± 0.03	1.31 ± 0.03	>0.10	>0.10	>0.10
Stance duration, s	0.86 ± 0.02	0.85 ± 0.02	0.88 ± 0.03	0.88 ± 0.03	>0.10	>0.10	>0.10
Swing duration, s	0.42 ± 0.01	0.42 ± 0.01	0.41 ± 0.01	0.43 ± 0.01	0.028	>0.10	0.037
Speed, m/s	1.21 ± 0.03	1.26 ± 0.03	1.17 ± 0.04	1.22 ± 0.04	0.004	>0.10	>0.10
Triple support, %	69.7 ± 1.4	66.9 ± 1.4	73.8 ± 2.0	68.6 ± 2.0	0.001	>0.10	>0.10

[1] *P*-values for the effects of surface (**S**: concrete vs. rubber), hoof health (**H**: nSU vs. SU), and their interaction (**SxH**).

Table 5.4 Least squares means ± SEM of subjective gait assessment on concrete and a composite rubber surface, for cows with no sole ulcers (nSU; n = 20) and cows with sole ulcers (SU; n = 10).

	nSU		SU		P^3		
Variable	**Concrete**	**Rubber**	**Concrete**	**Rubber**	**S**	**H**	**S*H**
Numerical rating system (NRS)[1]	2.5 ± 0.1	2.4 ± 0.1	3.1 ± 0.1	2.9 ± 0.1	0.010	0.003	>0.10
Back arch[2]	9 ± 2	11 ± 2	13 ± 2	12 ± 2	>0.10	>0.10	0.068
Head bob[2]	4 ± 1	6 ± 1	5 ± 1	5 ± 1	>0.10	>0.10	>0.10
Tracking up[2]	15 ± 2	11 ± 2	24 ± 2	19 ± 2	0.001	0.008	>0.10
Joint flexion[2]	27 ± 2	23 ± 2	33 ± 2	29 ± 2	0.003	0.023	>0.10
Asymmetric gait[2]	25 ± 2	23 ± 2	36 ± 3	31 ± 3	0.016	0.006	>0.10
Reluctance to bear weight[2]	7 ± 2	6 ± 2	16 ± 2	12 ± 2	0.022	0.009	>0.10
Abduction /adduction[2]	22 ± 2	18 ± 2	25 ± 3	23 ± 3	0.007	>0.10	>0.10

[1]Numerical rating system scored on a 5-point scale from 1 to 5, where 1 = sound and 5 = severely lame.

[2] Variables were scored on continuous 100-unit visual analog scales. Both ends of the scale had a description of the extreme forms of the condition. For example, degree of back arch had "flat" at one end (0) of the scale and "convex" at the other end (100), where "convex" represented the most extreme back arch the observer had seen in their experience.

[3] *P*-values for the effects of surface (**S**: concrete vs. rubber), hoof health (**H**: nSU vs. SU), and their interaction (**SxH**).

Figure 5.1 Mean difference (concrete minus rubber) in a) stride length (r = -0.51, $P < 0.01$), b) proportion of time in triple support (r = 0.59, $P < 0.001$), and c) stride overlap (r = -0.50, $P < 0.01$) plotted against mean overall gait score (NRS) for cows walking on concrete (n = 30).

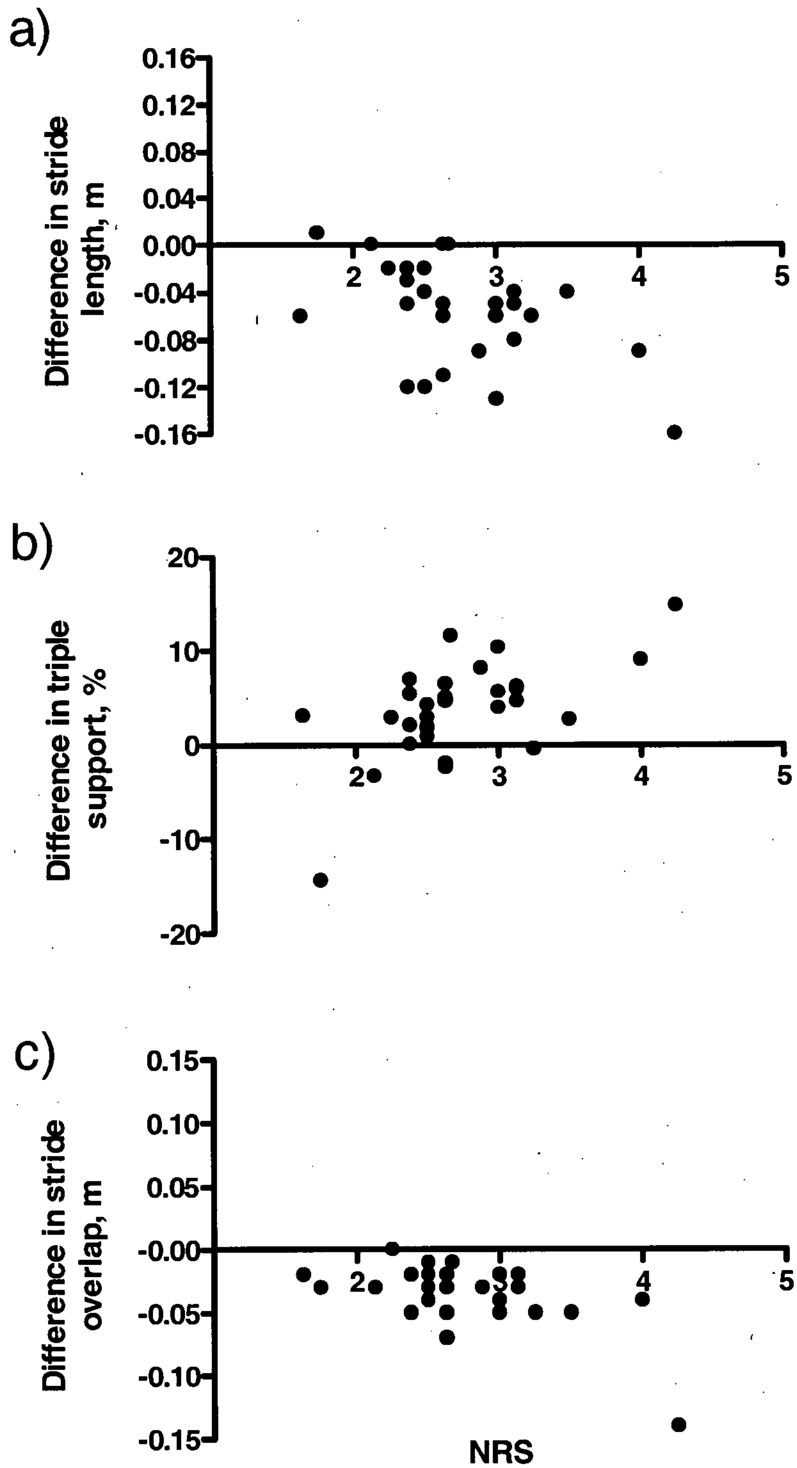
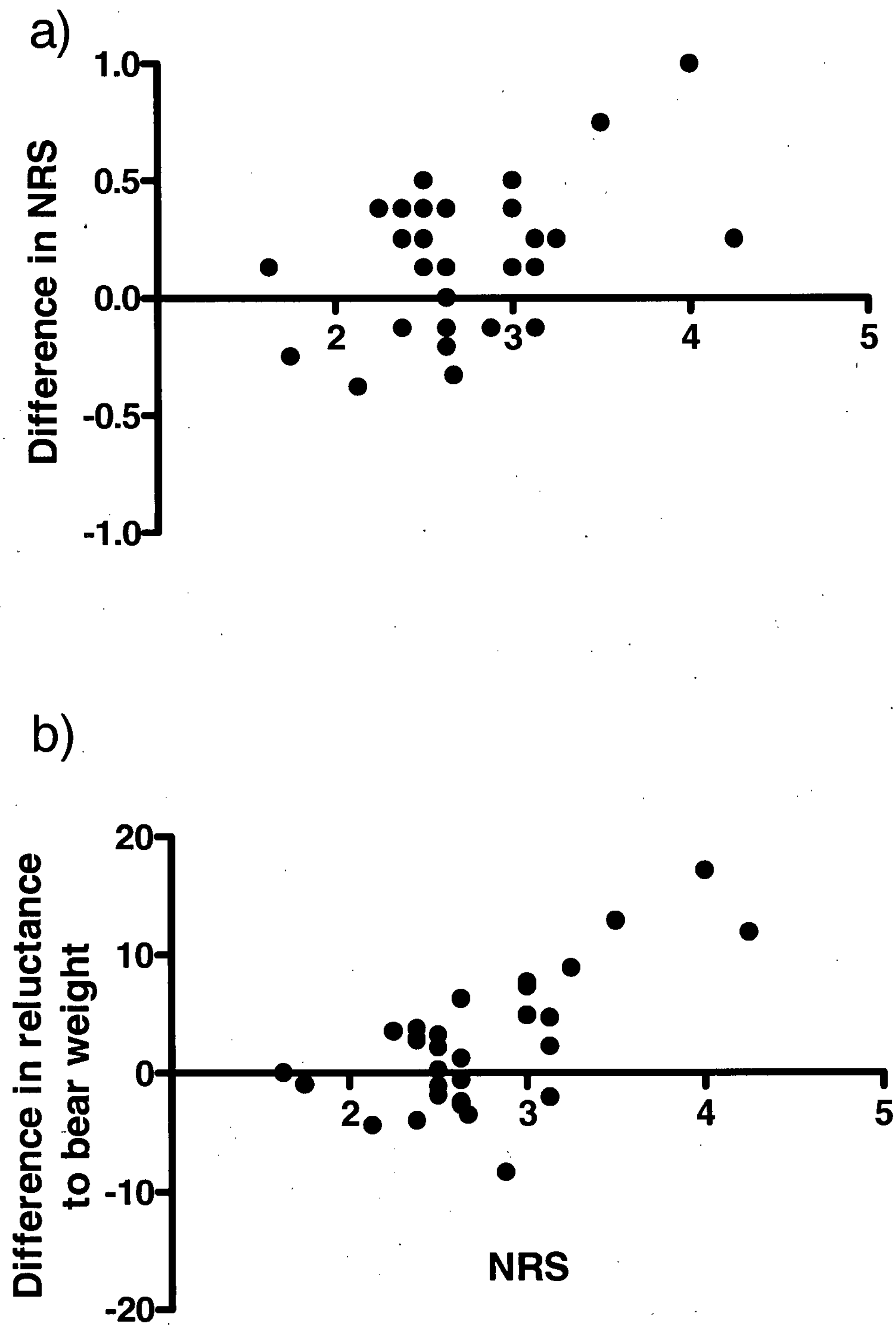


Figure 5.2 Mean difference (concrete minus rubber) in a) overall gait score (NRS; r = 0.46, $P < 0.01$) and b) reluctance to bear weight (r = 0.66, $P < 0.001$) plotted against mean overall gait score (NRS) for cows walking on concrete (n = 30).



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CHAPTER 6: Implications and Future Directions

6.1 Research findings

In today's dairy industry, producers manage many aspects of a dairy cow's life with the goal of maximising milk yield. For instance, producers decide how frequently cows are milked, when and what they are fed, which bulls they are bred to, and if they have access to pasture. However, keeping cows healthy is a constant battle even with major advances in veterinary medicine (LeBlanc et al., 2006). Herd health plans, developed between producers and veterinarians, encourage proactive intervention such as vaccination programs and maintaining closed herds to prevent the introduction of new diseases, and managing existing diseases through early identification and treatment of affected cows. However, even when such measures are taken, large numbers of dairy cows still suffer from ailments such as hoof pathologies.

Dairy cattle are affected by a wide range of hoof and leg pathologies. Early detection can be hampered by differences in the time course of development of different hoof pathologies, but also the use of poorly defined and un-validated gait scoring systems has proved inadequate at detecting cows with pathologies to date. To address this problem, my thesis explored different approaches to assessing and identifying cows with hoof pathologies, and also examined variables that may influence the way cows walk. The first major finding from my research (Chapters 2 and 3) was that both kinematic gait analysis and subjective gait assessment showed cows with no visible hoof pathologies walked differently from cows with sole ulcers. These differences in gait were likely due to cows reducing the load on an affected hoof. In Chapter 2, kinematic gait analysis demonstrated that cows with sole ulcers walked more slowly, had longer stride durations, shorter strides, and longer periods of triple support than cows with no visible hoof pathologies. In Chapter 3, subjective gait assessment showed that cows with sole ulcers also walked with a more pronounced back arch, jerky head movement, and more uneven weighting among limbs than cows with no visible hoof pathologies. Intra- and inter-observer reliability of these gait assessment behaviours was high, and the overall method was able to classify 92% of cows into the correct hoof health category.

The second important finding of my research was that cow factors (e.g., milking) and environmental factors (e.g., flooring) also affected how cows walk. After milking, when the udder was empty, cows had longer strides, higher stride height, shorter stride durations, walked faster and had shorter periods of triple support. Tracking-up and reluctance to bear weight also improved after milking. These differences before and after milking were probably due to udder distension and motivation to return to the pen. Furthermore, the effect of sole ulcers on gait was most evident after milking; this suggests that identifying cows with ulcers would be easier at this time.

Flooring surfaces also influenced cow gait. Cows walking on rubber flooring had longer strides, higher stride height, walked faster, had shorter periods of triple support and more stride overlapping than cows walking on concrete. In addition, cows walking on rubber had greater tracking-up, less reluctance to bear weight, greater joint flexion, more symmetric gait, and lower overall gait scores than cows walking on concrete. These differences were more evident for cows with higher gait scores. The findings suggest that rubber flooring provided more secure footing and was more comfortable for cows to walk on than concrete, probably because the rubber surface reduced the rate at which weight was loaded onto the hoof.

Surprisingly no differences were found between the gait of cows with sole haemorrhages and cows without visible hoof pathologies. One explanation is that these injuries were not painful (see section 6.4.1 for further discussion); however it is also possible that this lack of effect may have been due to problems with the way pathologies were scored. For example, the time course of haemorrhage development (from insult until the lesion is visible on the surface of the hoof) was estimated to be 8-10 wk, but it is possible that the actual time course was either shorter or longer under the conditions cows were kept in the current studies. Also, real differences may have been masked by the way data were analyzed. I averaged data across hooves to get 1 value per cow and included cows with any sole haemorrhage, regardless of severity, because the sample sizes were too small to meaningfully analyse injury by claw, hoof or severity. Examination of a few individual case studies suggests that injuries can affect hooves and gait in different ways. For example, Cow 45 from the Agassiz data set (Chapters 2, 3 & 4) had a severe sole haemorrhage on the right rear hoof and the maximum stride height of that hoof was (mean ± SD) 8.4 ± 0.6 cm; however the maximum stride height averaged across 4 hooves was very similar to the mean for cows with no visible hoof pathologies (9.9 ± 1.4 vs. 9.6 ± 1.9 cm, respectively).

6.2 Research implications

Kinematic gait analysis and subjective gait assessments were used to describe gait profiles of cows with no visible hoof pathologies, those with sole haemorrhages, and those with sole ulcers. Although this thesis suggests that both approaches are effective research tools, the work also raises several implications for future lameness research.

Research to date has suffered from poor and ambiguous definitions, often grouping different pathologies and effects together under the umbrella term lameness. My work demonstrated that different hoof pathologies (e.g., ulcers versus haemorrhages) have different effects on gait and supports the argument in Chapter 1, that researchers should refer to specific pathologies and effects wherever possible and avoid classifying cows simply as lame or not lame.

The application of kinematic gait analysis to dairy cow locomotion was a novel contribution to describing how cows walk and how they responded to specific hoof pathologies. Some studies have used other approaches to obtain quantitative stride measures; Telezhenko and Bergsten (2005) marked cow hooves with lime powder and slurry to leave imprints on flooring that could be measured, and Phillips and Morris (2001) timed cows walking along an alley of known length to record speed. Other work has used motion analysis software to record strides of cows housed in different management systems (Herlin and Drevemo, 1997) and to determine spatial requirements for cattle lying down (Ceballos et al., 2004). However, to my knowledge, this study was the first to use computer-aided kinematic techniques to a) record dairy cattle movement for studying the effects of hoof pathologies and b) quantify the stride cycle for dairy cattle. Most kinematic measures detected gait differences due to cow factors (i.e., milking; Chapter 4) and environmental factors (i.e., flooring surface; Chapter 5). Kinematic measures were also effective at distinguishing between cows with and without sole ulcers in one study (Chapter 2), but in a second study (Chapter 5) these measures were less useful.

Scoring systems have been developed over the last few decades to identify lame cows (Manson and Leaver, 1988; Whay et al., 1997, Juarez et al., 2003; Telezhenko and Bergsten, 2005). In particular, Sprecher et al.'s (1997) system, emphasising back arch as the measure to detect lame cows, has become popular. Interestingly, the validity of this system has never been established. Recently Amory et al. (2006), using an adapted version of Sprecher et al.'s (1997) locomotion system, argued that using a simple system improved assessment of lameness because it was easy to use and quick to train assessors. Although a practical system that is quick for assessors to learn is important, the resulting scores are of little value if they do not relate to specific ailments. Furthermore, little work has examined whether subjective gait assessment techniques are scored consistently between observers or even by the same observer. This thesis provides a fresh contribution: it is the first to explicitly define, validate and test the reliability of a series of cow gait measures. I found that most gait measures were valid. For example, animals with high scores for tracking-up and reluctance to bear weight were more likely to have sole ulcers. Most measures were also scored consistently; however, observers found some behavioural measures (e.g., joint flexion, asymmetric gait, and abduction/adduction) more difficult to evaluate and this suggests that in future these measures should be used with caution.

My results indicate that an overall assessment of gait, including several component behaviours, appears to be a better way to identify cows with sole ulcers than relying on a single behaviour like back arch. Indeed, several cows from the datasets in this thesis would be misclassified using Sprecher et al.'s (1997) back arch system for identifying lame cattle. For example, in this thesis, 3 out of 24 cows with no visible hoof pathologies (13%) had a pronounced back arch and 8 out of 17 cows with sole ulcers (47%) had minimal back arch. In contrast, relatively few cows were misclassified (8%) using the overall subjective gait assessment system in Chapter 3. Thus, future studies should move toward using scoring systems that take into account various gait-related behaviours, such as the NRS used in this thesis (Chapters 3-5).

No previous work, to my knowledge, has investigated specific relationships between kinematic and subjective measures. My work provided an insight into one aspect of gait (Chapter 5). Overlapping of front and rear hooves was recorded using both kinematics (stride overlap) and subjective gait assessment (tracking-up), and found that the subjective measure proved more useful in identifying cows with sole ulcers. I encourage future researchers to create and evaluate new, derived kinematic measures that capture important variation, currently captured by subjective measures like asymmetry, and ideally capture gait impairments in new and potentially more useful ways.

This thesis was the first study to use kinematic measures to assess gait of dairy cows with and without hoof injuries and found that this approach effectively detected responses to milking and flooring. Although the basic kinematic measures were able to distinguish cows with sole ulcers in Chapter 2, these measures failed to identify cows with sole ulcers in Chapter 5. This thesis was also the first study to subjectively assess a number of gait attributes separately and found that this approach was also effective at detecting the effects of milking and flooring. Furthermore, in both Chapters 3 and 5, the subjective measures consistently identified cows with sole ulcers. The results in this thesis suggest that the subjective measures may be of more general use in detecting cows with sole ulcers than kinematic measures. However, development of derived kinematic measures may be able to better capture gait impairments associated with hoof injuries. On this note it is of interest that derived measures reported in Chapters 4 and 5 such as stride overlap, time in triple support, and speed tended to be more useful in detecting treatment differences than basic kinematic measures like stride duration.

6.3 Practical implications

Kinematic analysis can provide a good research tool for describing how cow gait responds to treatments, but the method requires sophisticated technology that limits practical use on farms. It is possible that technological advances such as marker free systems (Green et al., 2000) would allow on-farm applications in the future, but currently kinematic gait analysis is most useful as a research tool.

Subjective gait assessments are more practical for field use, as they can be conducted on-site with no technical equipment. My work has shown that the subjective gait assessment used in this thesis can be applied reliably and be used to provide a valid indication of which cows have sole ulcers. For example, based on the results in Chapter 3, dairy professionals using the overall gait assessment could classify 92% of cows correctly into those with and without sole ulcers. Using this system, producers and other dairy professionals can monitor the number of cows with sole ulcers in a herd, and use this information to set specific goals for reducing the number of cows affected by these pathologies.

This thesis also informs observers about when and what to consider when conducting gait assessments. Evaluating cows at different times (before or after milking) or on different surfaces (concrete versus rubber) will influence the outcome of an assessment and could result in misclassification of cows or confound comparisons between herds. The importance of standardised animal welfare indicators was raised in the recent EU Action Plan on the Protection and Welfare of Animals (CEC, 2006). Indeed, if subjective gait assessments were used to identify the prevalence of sole ulcers on farms, comparisons would only be fair if assessments were either standardised (e.g., all evaluated after milking, on concrete) or factors that influence gait (e.g., milking and flooring) were accounted for in a statistical model. Other factors, such as breed, age, and hoof conformation, may also influence gait assessment, although more work is required to understand what effects these factors have on gait.

6.4 Future directions

My work has described a basic profile of how cows walk but there is still much work to be done to better understand how hoof and leg pathologies affect cows. The findings of my thesis have highlighted certain weaknesses in our current understanding of how cows respond to hoof injuries, and suggests that future research needs to focus on the following areas; a) pain and injury, b) leg injuries and disease, and c) flooring surfaces.

6.4.1 Pain and injury

In a recent UK survey, dairy professionals (veterinarians and hoof trimmers) considered lameness potentially painful (O'Callaghan-Lowe et al., 2004); however, there is little literature on the pain experienced by cows with hoof pathologies. Researchers can assess pain by measuring behavioural changes after applying a pain-relieving treatment (within-animal comparison) or by comparing the gait of cows with and without hoof pathologies (between-animal comparison). Although this thesis demonstrated gait differences between cows with and without sole ulcers, knowledge about which injuries are painful, and how the duration and location of injury affect pain responses, will help guide future research.

Various hoof injuries and diseases afflict dairy cattle; sole ulcers, sole haemorrhages, digital dermatitis, heel horn erosion, white line disease, and interdigital necrobacillosis are frequently found on farms in North America and Europe, but it is not clear how much pain is caused by these various ailments. Whay et al. (1998) suggested that different hoof lesions cause different intensities of pain; cows with sole ulcers are more sensitive to a painful stimulus (pin pressed into the metatarsus) than healthy cows (those with no hoof injuries), and cows with white line disease and digital dermatitis are even more sensitive. However, in Chapters 2 and 3, cows with sole haemorrhages walked similarly to cows without injuries, suggesting that sole haemorrhages were not sufficiently painful to affect gait. It is also possible that the gait measures used were only effective at detecting higher intensities of pain or that grouping all haemorrhages together masked effects. One way to assess whether injuries are painful is to measure changes in behaviour when pain-relieving analgesics or anaesthetics are provided. For example, both Sedlbauer (2005) and Rushen et al. (2006) found an improvement in gait scores of lame cows when an analgesic or local anaesthetic was administered, and although neither study specifically assessed hoof injuries, they demonstrate the potential for this type of research.

Once researchers have established which injuries are painful, the next challenge is to understand the time course of injury development in relation to pain, particularly for longer lasting hoof lesions. Some work has documented that sole and white line haemorrhages take 8-9 wk to become visible on the hoof (Bergsten and Frank, 1996; Leach et al., 1997). However, no research to date has documented when an injury is actually painful and how long the pain lasts. One potential approach to this challenge would be to record cow gait and the development of hoof injuries over a period of months. In addition, hoof growth and wear rates influence how quickly injuries become visible and should also be accounted for.

Dairy cows rarely suffer from a single hoof injury and most cows in this thesis had multiple injuries on multiple hooves. To date, no studies have examined how the location of hoof pathologies affect gait. As single hoof injures are rare, it is helpful to study individuals when the opportunity arises. For example, the maximum stride height of Cow 3 (Agassiz dataset, Chapters 2-4) with an ulcer on a rear hoof was lower for the injured and contralateral hoof than cows with no visible hoof pathologies (7.6 vs. 10.4cm, 7.3 vs. 9.7cm) and the ipsilateral hoof swung 4.1cm lower mid-stride. In contrast, Cow 14 (Lennoxville dataset, Chapter 5) had an ulcer on a front hoof and the injured and contralateral hoof swung 2.4 and 1.7 cm lower than for cows with no visible hoof pathologies, and rear hoof trajectories did not differ. These case studies indicate that ulcers on the front versus rear hoof have different effects on gait and these patterns likely become increasingly complicated as more hooves are affected. For some measures, the link between changes in behaviour and pain reduction is clear. For example, to reduce loading an injured leg, cows with sole ulcers spent longer with their weight distributed among 3 legs during the stride (i.e., increased duration of triple support) in comparison to cows with no visible injuries (Chapter 2). However, it is more difficult to explain why cows with sole ulcers had lower stride height (described in the case studies above) and illustrates the need for more detailed work on the effects of specific injuries and combinations of injuries. One interesting method to detect responses to injuries on different hooves is the use of force plate systems that monitor changes in weight-bearing (e.g., Neveux, 2005). Kinematic gait analysis can also be used to explore how leg joint angles change during the stride (e.g., Herlin and Drevemo, 1997). Such technologies may help to understand how cows respond to single and multiple hoof injuries in different locations.

In summary, future work needs to: a) identify which injuries are painful; b) investigate when injuries are painful and how long they last; and c) build profiles of cows with injuries on specific hooves to understand how injury location affects cow gait and other responses.

6.4.2 Leg injuries and disease

A survey from almost 30 years ago, reported that 12% of lameness in dairy cattle was caused by leg problems (Russell et al., 1982). Since this time almost all lameness research has focused on the hoof, and leg injuries and disease have received little attention.

Although legs were not clinically assessed, many cows in this thesis walked stiffly suggesting possible joint problems further up the leg. There are several technologies available to diagnose leg injuries in dairy cows. For example, ultrasonography evaluates soft tissue damage (muscles, tendons, ligaments, and joint capsules), radiology assesses bone structure and lesions, and infra-red thermography detects inflammation through surface temperature recording. These technologies provide good research tools for diagnosis of leg injuries, especially for studies investigating how such leg problems affect gait. However, it is unlikely that producers would use this technology due to the high costs involved. Producers and other dairy professionals may be able to identify leg injuries or disease through subjective gait assessments, although validity still needs to be established and the system possibly refined.

To date, much research has focussed on developing management systems that prevent hoof injuries (e.g., comfortable flooring surfaces, regular hoof trimming, and frequent footbaths). With successful systems in place to minimise hoof problems, the current lifespan of cows (4 yr;

Caraviello et al., 2004) may begin to increase. However, as cows grow older, other problems arise. For example, degenerative joint disease and osteochondrosis (a bone and cartilage disorder) are common ailments of older cattle and may become more prevalent in the future (Weaver, 1997; Tryon and Farrow, 1999). Tyron and Farrow (1999) identified that Holstein cattle housed on concrete are more prone to osteochondrosis than other breeds or cows housed on other surfaces. A thorough investigation of the risk factors associated with leg injuries and disease, such as breed, growth rate and flooring type, is now required.

In summary, future work needs to: a) assess the extent of leg injuries and disease in dairy cattle; b) evaluate whether subjective gait assessments and kinematic gait analysis tools can effectively detect cows with such injuries; and c) identify risk factors associated with these leg injuries and disease.

6.4.3 Flooring surfaces

Over the last few years, the use of rubber flooring has begun to increase in the dairy industry. Manufacturers claim that rubber surfaces improve hoof health (Animat Inc., 2006; Gabel Belting Inc., 2006; Humane Manufacturing, 2006), but there is little scientific evidence to substantiate these claims. Some recent literature reported fewer hoof injuries when cows were housed on rubber versus concrete (Vokey et al., 2001).

Telezhenko and Bergsten (2005) found that rubber improved the way cows walked. In this thesis, flooring also influenced the gait of cows; however it was unclear which properties of the flooring surface (e.g., friction, softness, abrasiveness, and surface profile) were important. Some work is emerging in this area. For example, Phillips and Morris (2001) reported that the optimal coefficient of friction for cows walking on concrete was approximately 0.4-0.5, and Rushen and de Passillé (2006) found that increasing the compressibility of a surface resulted in cows walking faster and slipping less.

It is possible that some flooring features might conflict with human safety standards for walking and standing surfaces. For example, floors with a coefficient of friction less than 0.5 are considered “inherently dangerous” for human workers (ASSE, 2002), yet Phillips and Morris

(2001) suggested cows walk better on surfaces below this value. Coefficients of friction for solid concrete flooring in barns currently range from 0.36 (Rushen and de Passillé, 2006) to 0.58 (Telezhenko and Bergsten, 2005). In any event, conflicts between desirable surfaces for cows and suitable surfaces for human handlers need to be resolved.

Another area to explore is whether it is necessary to install a particular flooring surface throughout the entire barn or if it is adequate to provide this surface in high-traffic areas only (e.g., at the feed bunk and the alley to the parlour), especially given the cost of materials. To date, this has not been investigated from a long-term hoof health perspective although short-term preference work has shown that cows will stand or walk on a softer surface given the option. For example, Tucker et al.'s (2006) study showed that cattle prefer standing on a softer surface at the feed bunk and Gregory and Taylor (2002) demonstrated that cows walking from pasture to the parlour showed a distinct preference for a wood-chip overlay versus a normal hard track surface.

An additional concern is that using soft flooring increases the likelihood of cows lying on these surfaces and not in designated stalls. This is a problem in part because the cow increases her risk of exposure to mastitis by lying in manure containing mastitis-causing organisms (LeJeune and Kaufmann, 2005). However, it is likely that this problem has more to do with the design of stalls and stocking density, than the flooring surface itself. For example, Tucker et al. (2003) found cows strongly preferred stalls with deep bedding to rubber mattresses; this suggests that softer walkways should not be a problem if stall comfort is adequate. Indeed, stall design is a hot topic in the dairy industry, often referred to as "cow comfort", and is primarily concerned with encouraging maximum lying times by making the lying environment as comfortable as possible. Often dairy professionals will assess the level of comfort in a barn using a cow comfort index (essentially measuring the proportion of cows lying down in stalls) (Cook et al., 2005). The same principle could be applied to the standing and walking surfaces, although, until now, flooring has largely been ignored. Given the relationships between flooring surface, hoof injuries and gait, standing and walking surfaces should be included in future cow comfort studies and incorporated into indices of cow comfort.

The financial implications and potential welfare issues associated with using a particular flooring surface indicate that more work is needed to investigate flooring surfaces before researchers can provide recommendations. Specifically, future work needs to: a) explore which components of flooring are best for cows; b) investigate where this flooring should be installed; and c) consider including flooring in cow comfort studies and indices. For research purposes, future studies should also describe details on friction, softness, etc. to enable comparisons across studies, as currently most reports provide minimal descriptions of the flooring used.

6.5 Summary

James Herriot and David Morrow wrote about their encounters with lame cows over 40 years ago. In the intervening years lameness has become more prevalent and is now considered the major health issue for the dairy industry (Gröhn et al., 2003). Although dairy professionals consider lameness painful, less than a third of veterinarians use analgesics when treating lame cattle, probably because of expense and milk withdrawal (O'Callaghan-Lowe et al., 2004). Methods of detecting ailments at an early stage are required, particularly as cows with severe injuries are unlikely to be given pain relief. My thesis explored 2 methods designed to profile gait, and found the kinematic measures were able to identify gait impairments associated with sole ulcers in the first dataset, but the subjective gait assessments were consistently able to do so in both datasets. My work also found that milking and flooring surface influenced both types of gait measure and should be considered in future gait assessments. However, many research questions remain unanswered. In this final Chapter I have outlined some of the research areas that need to be explored in more detail. Specifically, more work is needed to quantify the severity and duration of pain related to hoof pathologies, to examine the extent of leg injuries and disease and their effects on gait, and to develop alternative flooring that benefits hoof health and is practical on farms. My hope is that the research described here provides the first of many positive steps on the long journey toward reducing painful hoof and leg pathologies in dairy cattle.

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Appendix 1: Animal Care Certificate

The University of British Columbia

ANIMAL CARE CERTIFICATE

PROTOCOL NUMBER: **A00-0296**

INVESTIGATOR OR COURSE DIRECTOR: **Weary, D.M.**

DEPARTMENT: **Animal Science**

PROJECT OR COURSE TITLE: **Lameness in Dairy Cattle**

ANIMALS: **Cattle 500**

START DATE: **01-01-01** APPROVAL DATE: **2002-01-28**

FUNDING AGENCY: **Dairy Farmers of Canada**

The Animal Care Committee has examined and approved the use of animals for the above experimental project or teaching course, and have been given an assurance that the animals involved will be cared for in accordance with the principles contained in Care of Experimental Animals - A Guide for Canada, published by the Canadian Council on Animal Care.

Approval of the UBC Committee on Animal Care by one of:
Dr. W.K. Milsom, Chair
Dr. J. Love, Director, Animal Care Centre
Ms. L. Macdonald, Manager, Animal Care Committee

This certificate is valid for one year from the above start or approval date (whichever is later) provided there is no change in the experimental procedures. Annual review is required by the CCAC and some granting agencies.

A copy of this certificate must be displayed in your animal facility.

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323-2194 Health Sciences Mall, Vancouver, V6T 1Z3
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The University of British Columbia

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INVESTIGATOR OR COURSE DIRECTOR: **Weary, D.M.**

DEPARTMENT: **Animal Science**

PROJECT OR COURSE TITLE: **Lameness in Dairy Cattle**

ANIMALS: **Cattle 500**

START DATE: **01-01-01** APPROVAL DATE: **January 27, 2003**

FUNDING AGENCY: **Dairy Farmers of Canada**

The Animal Care Committee has examined and approved the use of animals for the above experimental project or teaching course, and have been given an assurance that the animals involved will be cared for in accordance with the principles contained in Care of Experimental Animals - A Guide for Canada, published by the Canadian Council on Animal Care.

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