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Gait assessment in dairy cattle

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Lameness is one of the most important dairy cow welfare issues and has inspired a growing body of literature on gait assessment. Validation studies have shown that several methods of gait assessment are able to successfully distinguish cows with and without painful pathologies. While subjective methods provide an immediate, on-site assessment and require no technical equipment, they show variation in observer reliability. On the other hand, objective methods of gait assessment provide accurate and reliable data, but typically require sophisticated technology, limiting their use on farms. In this critical review, we evaluate gait assessment methods, discuss the reliability and validity of measures used to date, and point to areas where new research is needed. We show how gait can be affected by hoof and leg pathologies, treatment of these ailments and the pain associated with lameness. We also discuss how cow (e.g. conformation, size and udder fill) and environmental features (e.g. flooring) contribute to variation in the way cows walk. An understanding of all these factors is important to avoid misclassifying of cows and confounding comparisons between herds.

Keywords: cattle, lameness, locomotion, validity, welfare

Introduction

Research on gait in cattle has largely been driven by an interest in detecting lameness. Lameness, defined as a deviation in gait resulting from pain or discomfort from hoof or leg injuries and disease, can affect many cows (some studies have reported prevalence of up to 55%; Clarkson *et al.*, 1996), reduces milk production, feed intake and fertility and is costly for producers (Green *et al.*, 2002; O'Callaghan, 2002; Hernandez *et al.*, 2005). Most gait evaluations assess changes relative to 'normal gait', but such changes can be difficult to judge; Whay *et al.* (2003) reported that producers identified only one of every four cases of dairy cattle with hoof injuries or disease, and another study found that only one of every three cows were correctly identified (Espejo *et al.*, 2006). The stoic nature of cattle means that even painful pathologies of the hoof or leg may cause little or no obvious changes in behaviour, and some pathologies such as heel erosion may cause little pain, at least in early stages of development. Subjective assessments can suffer from poor inter- and intra-observer reliability, problems that can be avoided by using objective kinetic and kinematic measures. However, the equipment used to collect these measures can be expensive and impractical for on-farm assessments. Both subjective and objective methods need to be validated to show how the values recorded relate to the presence of hoof and leg pathologies, and the pain and discomfort that these cause. The aims of this paper are to critically review the growing literature on gait assessment in cattle, discuss the reliability and validity of measures that have been used, and point to areas where new research is most needed.

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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 used: numerical rating scores (NRS), and to a lesser extent, visual analogue scales (VAS). NRS rate individual cows, typically on a five-point scale, for the presence or absence of certain behaviours and postures related to gait. The first NRS used in dairy cattle research was on a 1 to 5 scale (with half points) with scores assigned by observers according to the criteria in Table 1 (Manson and Leaver, 1988). Interpreting the Manson and Leaver system can be difficult, for instance, the terms slight, some and obvious will depend on the previous experiences of the observer, perhaps explaining why few research papers use this system today. More recently, some authors have created simpler scoring systems by using only one or two specific behaviours.

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For example, the Sprecher system (Sprecher *et al.*, 1997; Table 2) is popular due to its simplicity, and largely relies on the observation of the presence of an arched back when standing and walking. The validity of this system has never been established, but the original idea may date back to Morrow (1966) who anecdotally described a case of a lame cow that stood with an arched back. The issue of validity of subjective measures will be discussed in more detail in the next section.

VAS were developed for use by human patients to rate pain (Scott and Huskisson, 1976), and consist of a horizontal line with a description of the extremes at either end of the scale. VAS have been adapted for lameness assessments so that an observer marks on the line the perceived condition of the animal between 'sound' and 'could not be more lame'. 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 restricting scores to discrete units.

Validity of subjective measures

One approach to validating scoring systems is to compare gait in animals with and without known hoof and leg pathologies. Previous studies have reported weak to modest relationships between scores and measures of hoof and leg injuries or disease. For example, a series of studies have shown that the presence of sole lesions accounted for 20% to 70% of the variation in gait scores (Whay *et al.*, 1997; van Eerdenburg *et al.*, 2003; Flower and Weary, 2006).

Another way to identify valid lameness measures is to compare animals with or without a treatment known to reduce hoof or leg injuries. The positive effects of access to pasture on hoof health are well documented; cows kept indoors have a greater prevalence of claw disorders than those allowed to graze (Smits *et al.*, 1992). Thus, one approach to validating lameness assessment measures is to compare gait in animals with and without pasture access. In one study, Hernandez-Mendo *et al.* (2007) compared a matched sample of lame cows, kept for 5 weeks either in a freestall barn or on pasture. The NRS improved rapidly for the cows on pasture but the NRS for cows kept indoors showed no improvement. This clear effect of treatment was also apparent using some specific gait attributes (like reluctance to bear weight), but there was no effect of treatment on other gait attributes like back arch or head bob.

Although subjective methods may be well 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 number of animals), one observer's assessment may differ from another's or even from his own assessment conducted on another occasion. We turn to the issue of reliability below.

Reliability of subjective assessments

Martin and Bateson (1998) defined the reliability of a variable as the extent to which it is precise and consistent. Both the observer and the scoring system may affect the reliability of subjective methods of gait assessment. Hollenbeck (1978) suggested that observers could affect the repeatability of a study in a number of ways. Firstly, results 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

Table 1 *A numerical rating system (NRS) for dairy cattle locomotion (from Manson and Leaver, 1988)*

Gait 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

Table 2 *A numerical rating system for dairy cattle locomotion (from Sprecher* et al.*, 1997)*

Gait score	Clinical description	Assessment criteria
1	Normal	The cow stands and walks with a level-back posture. Her gait is normal
2	Mildly lame	The cow stands with a level-back posture but develops an arched-back posture while walking. Her gait remains normal
3	Moderately lame	An arched-back posture is evident both while standing and while walking. Her gait is affected and is best described as shortstriding with one or more limbs
4	Lame	An arched-back posture is always evident and gait is best described as one deliberate step at a time. The cow favours one or more limbs/feet
5	Severely lame	The cow additionally demonstrates an inability or extreme reluctance to bear weight on one or more of her limbs/feet

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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%. Finally, observer scores may change over time (Hollenbeck, 1978). Such 'observer drift' is especially a problem for live observations; researchers using video recordings are able to quantify drift by re-scoring the same tapes at different times.

Characteristics of the scoring system may also affect reliability. Some scoring systems use very general terms to categorize animals (e.g. 'sound, imperfect locomotion, mild lameness, moderate lameness and severe lameness'; Whay *et al.*, 1997), allowing more leeway among observers, and others use more detailed descriptions of the behaviours (e.g. Whay, 2002). 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 two 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 (2001) reported 68% agreement between three observers simultaneously evaluating the gait of dairy cattle ($n = 147$) using a five-point NRS (Table 3). However, most disagreements (30%) differed by only one category and the authors argued that these differences would not result in misjudging animals. Similar levels of inter-observer repeatability were also demonstrated by Manson (1986; $r = 0.84$) and Flower and Weary (2006; $r = 0.83$), suggesting that observers will rarely be in total agreement when assessing gait.

The scoring methods described above rely on an overall evaluation of the animal's condition, involving simultaneous evaluation of several behaviours. In general, there has been little attempt to justify the inclusion of specific behaviours like back arch. An alternative approach is to score specific behaviours separately. For example, in one study we scored six specific behaviours (head bob, back arch, tracking-up, joint flexion, asymmetric gait and reluctance to bear weight) using a VAS, allowing us to assess the reliability for each behaviour (Flower and Weary, 2006). Some of the behaviours could be scored with a high inter- and intra-observer reliability (e.g. tracking-up; $r = 0.91$ and 0.95, respectively), but other behaviours proved more difficult to score consistently (e.g. joint flexion; $r = 0.62$ and 0.75, respectively). Even for those behaviours that could be scored with reasonable reliability, agreement was best for the higher scores, with low and intermediate scores showing poor consistency (Flower and Weary, 2006).

Effect of training and experience

Recent work has demonstrated that newer subjective assessments are more reliable. For instance, Brenninkmeyer *et al.* (2007) tested three types of scoring systems and found good inter-observer agreement when a two-category scoring system was used (lame or not lame; prevalence adjusted bias adjusted kappa (PABAK) coefficient value = 0.70) but less agreement when a five-category system was applied (PABAK = 0.53; Table 3). Importantly, the authors found that agreement improved over time (i.e. with more experience observers were more likely to agree). This finding was mirrored in March *et al.*'s (2007) study where the PABAK value between an experienced and an initially inexperienced observer was 0.53 on the first occasion but improved to 0.88 after scoring 49 farms with the five-category system. Furthermore, March *et al.* (2007) reported that to achieve a good level of reliability, at least 200 to 300 cows need to be used to train an observer.

Issues of reliability also plague clinical scores used to evaluate hoof health. Holzhauer *et al.* (2006) showed that trimmers varied greatly in scores for disorders such as digital dermatitis (presence or absence) and interdigital dermatitis/heel horn erosion and sole haemorrhages (graded on four-point scales). This variation may be a result of the individual experience, scoring system or the conditions at the time of trimming (e.g. poor lighting). Like gait scoring systems, some existing lesion scoring systems provide well-defined categories for different stages of hoof disease (e.g. classes

Table 3 *A numerical rating system for dairy cattle locomotion with five, four and two categories (from Brenninkmeyer* et al.*, 2007)*

Gait score	Five category description (originally from Winckler and Willen, 2001)	Four category description	Two category description
1	Normal gait	Non-lame	Non-lame
2	Uneven gait (stiff/very careful/swinging of legs around the udder/swaying of trunk and/or hindquarters)		
3	Short striding gait with one limb (even if just noticeable)	Short striding gait with one limb (even if just noticeable)	Lame
4	Short striding gait with more than one limb or strong reluctance to bear weight on one limb	Short striding gait with more than one limb or strong reluctance to bear weight on one limb	
5	Does not support on one limb or strong reluctance to put weight on limb in two or more limbs, holding a limb up whenever possible	Does not support on one limb or strong reluctance to put weight on limb in two or more limbs, holding a limb up whenever possible	

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for digital dermatitis described by Döpfer *et al.*, 1997) and should promote consistency in future work.

In conclusion, current scoring methods are subjective in nature with varying reliability and validity. Ambiguous terminology used in previous scoring systems is now replaced with more detailed and specific definitions in an attempt to decrease measurement error. Observer biases, experience and drift can also influence reliability; hence new work is starting to provide refinements to these systems and document reliability of scoring systems to address such issues. Some work has attempted to validate these scoring systems in relation to pathology and treatment but this attempt has met with variable success. Another approach to assessing gait is to use sophisticated recording equipment to collect objective kinetic and kinematic data, avoiding the problems of variable inter- and intra-observer reliability inherent with subjective scoring systems. We review objective kinetic and kinematic gait assessment in the next section.

Objective methods of gait assessment

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 can measure horizontal and vertical forces exerted by hooves in contact with the ground and have been used successfully to assess forces involved in walking of dairy cows (Scott, 1988; Van der Tol *et al.*, 2002). Kinematics is the study of changes in the 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. Records are analysed using motion analysis software, capable of digitizing a sequence of movements automatically, and the data collected are used to calculate linear and angular displacements, velocity and acceleration of each marker (e.g. Peham *et al.*, 2001).

Both kinetic and kinematic techniques have practical applications for research on lameness. 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.

Validity of objective measures

The problems over reliability, discussed earlier for subjective methods, should not be as serious for objective methods, and can easily be quantified. However, validity is still a concern. For example, a force plate system used by Rajkondawar *et al.* (2006) has been proposed as a tool to detect 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 (2006) study correlated the force plate measures of walking cattle with gait scores as the measure of lameness, the paper did not report how forces varied with known hoof and leg pathologies. Neveux *et al.* (2006) investigated the weight distribution of standing cows using force plates. The authors found that cows with high hoof-injury scores 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.

Some specific gait measures have been successfully validated in some studies, but not in others. For example, we found that objective kinematic measures were valid indicators of sole ulcers in one study (Flower *et al.*, 2005), but not in another (Flower *et al.*, 2007). We have generally found that derived measures (stride overlap, time in triple support and speed) are more useful in detecting differences than basic kinematic measures like stride duration (Flower *et al.*, 2006 and 2007). Pastell and Kujala (2007) validated measures of force from cows standing in a robotic milker, modelling the data into a probabilistic neural network, against hoof lesions and gait scores, and found they could positively detect 100% lame cows with this technology. We suspect that sophisticated methods of data handling and analysing, like those reported by Pastell and Kujala (2007), will allow for better integration of objective data, and more powerful predictive models for detecting cows with hoof and leg pathologies.

Technical issues

Objective methods can be subject to technical difficulties that reduce their usefulness. 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 and increase the effort needed to move the limbs (Roepstorff and Drevemo, 1993).

Another 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 $\leqslant$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

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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. Other objective methods also show promise. For example, hand-held infra-red thermography devices are being explored as a way to detect changes in temperature around the hoof, indicative of hoof lesion development (Nikkhah *et al.*, 2005). More work is needed to determine whether this technology is valid and practical.

Relationships between subjective and objective measures

To our knowledge, only two studies have directly investigated relationships between objective and subjective gait assessment measures. One recent study compared a locomotion scoring system and a force plate system in detecting painful lesions (Bicalho *et al.*, 2007). The authors concluded that a trained veterinarian using a locomotion scoring system performed better than the force plate system. The five-point locomotion scoring system was more sensitive (67.5% *v.* 33.3%, respectively) but slightly less specific (84.6% *v.* 89.5%, respectively) than the force plate system.

Flower *et al.* (2007) examined the relationship between one subjective and one objective measure of gait, but in this case both measures were designed to assess the same basic gait attribute; the extent to which cows overlapped in the location of front and rear hoof placements when walking was measured using kinematics (stride overlap) and a subjective gait assessment (tracking-up). These measures were related, but variation in the kinematically assessed stride overlap accounted for only 26% of the variance in subjectively assessed tracking-up. This relatively weak relationship may have been because the two variables recorded different aspects of overlap: stride overlap was based on an average of the left and right sides, whereas tracking-up assessed both the left and right sides, but assigned a score based on the worst side. Moreover, subjective judgements of 'tracking-up' likely include more than just the quantitative relationship of hoof-fall positions. Which of these measures should be preferred will depend upon the information these provide about hoof and leg pathology and the pain and discomfort experienced by the cow.

The effects of pain on gait

In principle, pathologies such as a cartilage obstruction in the joint might affect gait (for e.g. by restricting the range of motion within that joint), without causing the animal pain or discomfort. The ailments of greatest welfare concern are those that cause pain. It seems likely that the reason why many ailments cause changes in gait is that they cause pain, and animals attempt to modify gait so as to reduce this pain. Despite the apparent importance of understanding the role of pain, very little work has examined how changes in gait relate to the pain cows experience while walking. 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 modern commercial dairy farms, but it is not clear how much pain is caused by these ailments. In some validation studies, pronounced changes in gait for cows with sole ulcers were observed, but not for those with sole haemorrhages, suggesting that the latter are less painful (Flower *et al.*, 2005; Flower and Weary, 2006). However, 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.

We also require a greater understanding of the underlying mechanisms in order to generate meaningful predictions. For some measures, the link between changes in behaviour and pain reduction is relatively clear. For example, in comparison to cows with no injuries, cows with a sole ulcer may be expected to reduce loading on the affected leg and redistribute weight among the other three legs (as evidenced, for e.g. by increased duration of triple support; Flower *et al.*, 2005). For other measures (such as stride height), it is less clear how the change in gait is expected to reduce the pain cows experience while walking.

A more explicit way of addressing the role of pain is to measure changes in behaviour when pain-relieving analgesics or anaesthetics are provided. For example, Rushen *et al.* (2007) found modest improvements in gait scores of lame cows when they were provided either a local anaesthetic. This approach can also be used to further address the validity of various scoring methods. Flower *et al.* (2008) found that the NRS showed a clear dose-dependent decline with analgesic treatment, but that for several specific gait features (e.g. tracking-up) there was no relationship with treatment. Further research is now required using cows with specific hoof and leg ailments, to determine the pain that these cause and how this pain affects gait.

An alternative approach to the issue of pain is to look for responses that generalize across injuries and locations. For example, a painful injury will sometimes increase the animal's sensitivity to other sources of pain. This 'hyperalgesia' response can be assessed by exposing the animals to a painful stimulus (such as mechanical pressure or heat) and measuring the withdrawal response. Whay *et al.* (1998) found that cows with sole ulcers showed more evidence of hyperalgesia than cows without hoof injuries. This study also found that this hyperalgesia response was even greater for cows with white line disease and digital dermatitis, indicating that these ailments are especially painful.

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Lastly, researchers need to carefully consider which measures of pain are appropriate for lameness studies. For example, Dyer *et al.* (2007) used hoof pressure testers as a way to measure pain. They found that cows that were sensitive to this pain assessment also had higher locomotion scores. However, the authors also found high locomotion scores and low sensitivity to pressure, as well as low locomotion scores and sensitive hooves (i.e. false negatives and false positives), suggesting that at least some of the variation in either the pressure or locomotion scores was not related to pain.

Effects of conformation and posture

Conformation refers to the physical dimensions and shape of a cow (Greenough *et al.*, 1997), and is typically evaluated on a nine-point scale for both production traits (such as udder depth) and non-production 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 likely have longer strides than smaller cows. In order to increase the ability to identify gait differences due to painful injuries, these size differences should be minimized or controlled for. For example, a study on broiler hens showed that expressing results as a percentage of each hen's body weight enabled comparisons between birds of different weights (Corr *et al.*, 2003). Unfortunately, few cattle gait studies have incorporated body size measures into kinematic-type analysis (e.g. Herlin and Drevemo, 1997). Body weights of cattle are highly variable, in part due to differences in gut and rumen fill, so measures such as leg length may be more appropriate to account for size differences. 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. Thus, comparisons involving animals highly variable in size (e.g. heifers *v.* cows) are most likely to benefit by including morphometric measures as covariates.

Posture may also affect gait. Posture refers to how a cow stands or moves and animals may assume certain postures to relieve pain. For example, Greenough *et al.* (1997) described that standing cows sometimes 'camp back' or 'camp forward', referring to the position of the hind legs in relation to a vertical line drawn from the pelvis, and suggested that cows used the postures to relieve pain in the toe or heel. Certain postures, such as perching (standing with the two front legs in a cubicle and the two hind legs in the alley), are seen frequently in loose-housed dairies. Pilot work by our group has found that perching accounted for 41% of the variation in the number of hoof lesions (Flower and Weary, 2002), although this does not show which (if either) variable plays a causal role in the relationship.

Cows may also assume a posture to adjust for mechanical influences, such as a full, heavy udder. In one study we monitored changes in cow gait (including stride length, height, duration, speed, triple support and tracking-up) for cows walking to and from the milking parlour (Flower *et al.*, 2006). Gait differed on the return from the parlour; for example, cows walked faster, used longer strides and had a shorter duration of triple support. These differences may have been in response to udder fill, or may have been due to cows being more motivated to return to their stalls (and fresh feed) after milking than when they were going to the parlour in the first place. New research is now required to better understand the effects of motivation on gait.

Environmental effects

Flooring surface, especially concrete, is 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; Platz *et al.*, 2007). For instance, 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 when walking on higher friction surfaces (0.65 *v.* 0.59 strides/s; 1.30 *v.* 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 *v.* 1.05 m/s).

Rubber is now being introduced as an alternative flooring surface in dairy barns. The surface is intended to benefit hoof health, but little is known about how rubber affects cow mobility. Telezhenko and Bergsten (2005) tested cows walking on solid and slatted concrete, solid and slatted rubber and wet, compressed sand. The authors concluded that rubber mats had a positive effect on locomotion. Flower *et al.* (2007) also found that cow gait improved (in terms of gait scores and kinematic measures) on a soft, higher friction rubber surface in comparison to concrete, particularly for cows with higher gait scores. Rubber flooring may provide more secure footing and more comfort than concrete, probably because the rubber surface reduces the rate at which weight is loaded onto the hoof.

Clearly, more detailed studies on the effects of flooring are needed, but results to date indicate that flooring can have profound effects on gait. This variation may pose a challenge for those conducting gait assessments on different farms. Other studies on the effects of environmental variation on gait also need to be studied. We suggest that social effects may be especially important; for example, gait likely differs when cows walk alone or in a group, and some gait features (like walking speed) are likely affected by the behaviour of others in the herd walking with the focal cow.

To summarize, differences in conformation, size, flooring and other cow and environmental features may account for

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much of the variation in the way cows walk. An understanding of these factors will be particularly important when conducting on-farm evaluations that require scoring cows at different times (e.g. before or after milking) and on different surfaces (e.g. concrete *v.* rubber); uncontrolled variation could result in misclassifying cows and confounding comparisons between herds. If gait assessments are used to compare farms, these factors should be standardised (e.g. all evaluated after milking, on concrete) or accounted for in the statistical model.

Experimental design considerations: within- and between-animal comparisons

To understand how hoof and leg pathologies affect gait, researchers often compare animals before and directly after imposing some form of treatment. 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 always 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% to 53%). Accurate recordings of gait characteristics may therefore require multiple measures; Corr *et al.* (1998) argued that a large number of tests are required to calculate one individual's gait profile with even modest precision.

Within-animal comparisons allow researchers to use the animal as its own control and thus avoid variation due to the animal factors described above. For example, previous studies on horses and other animals have recorded measures of gait from a sound animal and reported changes in these variables after an injury was '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 cattle where sole injuries can take approximately 8 weeks to become visible as haemorrhages or ulcers (Bergsten, 1994), meaning that researchers can never be certain whether a cow is free from injury.

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, 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 may be 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. This design allows each animal to act as its own control, although researchers still need to prevent carry-over effects by allowing sufficient time between treatments.

Another way to assess the effects of hoof and leg pathologies is to compare cows, although grouping together various pathologies can be a source of error in these between-animal comparisons. 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. More research is now required to understand how dairy cows respond to a single injury, such as a lesion on a specific limb. However, if studies are to use existing variation within the population (as opposed to experimentally induced injuries), they will likely require large sample sizes in part because few dairy cows are free of hoof or leg pathologies. As single hoof injures are rare, it is helpful to study individuals when the opportunity arises. We encourage researchers to begin documenting cases involving specific injuries.

Gait effects likely become more complicated as both the type and number of injuries increase. Force plate systems that monitor changes in weight bearing may be especially useful in detecting problems affecting a specific limb (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), and may help to understand how cows respond to single and multiple hoof injuries in different locations.

Conclusion

In this paper, we have critically reviewed the literature on gait assessment, providing some insight into the benefits and drawbacks associated with various methods and outlining areas that need to be explored further. An understanding of all these factors is important when conducting on-farm evaluations in order to avoid misclassifying cows and confounding comparisons between herds. Both subjective and objective gait assessment methods can be used to identify hoof and leg pathologies and the pain experienced by the cow. Subjective methods are 'farm-friendly'; they provide an immediate, on-site assessment and require no technical equipment, but only recently have systems documented observer reliability. Results from a few studies show that some subjective scores can be applied consistently within and among observers, especially if the

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scoring system provides detailed definitions of each category and the observers have been trained. Objective methods of gait assessment are 'lab-friendly'; they provide accurate and reliable data, but often require sophisticated technology, limiting their use on farms. Furthermore, objective and subjective methods may require multiple samples to overcome variations in gait. Ultimately, the choice of measure or combination of measures should depend on the type of information they can provide.

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References

Barrey E 1999. Methods, applications and limitations of gait analysis in horses. Veterinary Journal 157, 7–22.

Bergsten C 1994. Haemorrhages of the sole horn of dairy cows as a retrospective indicator of laminitis: an epidemiological study. Acta Veterinaria Scandinavica 35, 55–66.

Bicalho RC, Cheong SH, Cramer G and Guard CL 2007. Association between a visual and an automated locomotion score in lactating Holstein cows. Journal of Dairy Science 90, 3294–3300.

Brenninkmeyer C, Dippel S, March S, Brinkmann J, Winckler C and Knierim U 2007. Reliability of a subjective lameness scoring system for dairy cows. Animal Welfare 16, 127–129.

Buchner F, Kastner J, Girtler D and Knezevic PF 1993. Quantification of hind limb lameness in the horse. Acta Anatomica 146, 196–199.

Buchner HH, Savelberg HH, Schamhardt HC and Barneveld A 1996. Limb movement adaptations in horses with experimentally induced fore- or hind-limb lameness. Equine Veterinary Journal 28, 63–70.

Clarkson MJ, Downham DY, Faull WB, Hughes JW, Manson FJ, Merritt JB, Murray RD, Russell WB, Sutherst JE and Ward WR 1996. Incidence and prevalence of lameness in dairy cattle. The Veterinary Record 138, 563–567.

Corr SA, McCorquodale CC and Gentle MJ 1998. Gait analysis of poultry. Research in Veterinary Science 65, 233–238.

Corr SA, McCorquodale CC, McGovern RE, Gentle MJ and Bennett D 2003. Evaluation of ground reaction forces produced by chickens walking on a force plate. American Journal of Veterinary Research 64, 76–82.

Dijkman JT and Lawrence PR 1997. The energy expenditure of cattle and buffaloes walking and working in different soil conditions. Journal of Agricultural Science 128, 95–103.

Döpfer D, Koopmans A, Meijer FA, Szakáll I, Schukken YH, Klee W, Bosma RB, Cornelisse JL, van Asten AJAM and ter Huurne AAHM 1997. Histological and bacteriological evaluation of digital dermatitis in cattle, with special reference to spirochaetes and *Campylobacter faecalis*. The Veterinary Record 140, 620–623.

Dyer RM, Neerchal NK, Tasch U, Wu Y, Dyer P and Rajkondawar PG 2007. Objective determination of claw pain and its relationship to limb locomotion score in dairy cattle. Journal of Dairy Science 90, 4592–4602.

Espejo LA, Endres MI and Salfer JA 2006. Prevalence of lameness in high-producing Holstein cows housed in freestall barns in Minnesota. Journal of Dairy Science 89, 3052–3058.

Flower FC and Weary DM 2002. Lameness assessment in dairy cows: a comparison of quantitative and qualitative approaches. The Proceedings of the 12th International Symposium on Lameness in Ruminants, Orlando, USA, p. 416.

Flower FC and Weary DM 2006. Hoof pathologies influence subjective assessments of dairy cow gait. Journal of Dairy Science 89, 139–146.

Flower FC, Sanderson DJ and Weary DM 2005. Hoof pathologies influence kinematic measures of dairy cow gait. Journal of Dairy Science 88, 3166–3173.

Flower FC, Sanderson DJ and Weary DM 2006. Effects of milking on dairy cow gait. Journal of Dairy Science 89, 2084–2089.

Flower FC, de Passillé AM, Weary DM, Sanderson DJ and Rushen J 2007. Softer, higher-friction flooring improves gait of cows with and without sole ulcers. Journal of Dairy Science 90, 1235–1242.

Flower FC, Sedlbauer M, Carter E, von Keyerslingk MAG, Sanderson DJ and Weary DM 2008. Analgesics improve the gait of lame dairy cattle. Journal of Dairy Science 91, 3010–3014.

Garner J, Falcone C, Wakenell P, Martin M and Mench J 2002. Reliability and validity of a modified gait scoring system and its use in assessing tibial dyschondroplasia in broilers. British Poultry Science 43, 355–363.

Gentle MJ and Corr SA 1995. Endogenous analgesia in the chicken. Neuroscience Letters 201, 211–214.

Green LE, Hedges VJ, Schukken YH, Blowey RW and Packington AJ 2002. The impact of clinical lameness on the milk yield of dairy cows. Journal of Dairy Science 85, 2250–2256.

Greenough PR, McDaniel BT and Leipold HW 1997. Conformation, growth and heritable factors. In Lameness in cattle (ed. PR Greenough and AD Weaver), pp. 71–86. WB Saunders Company, Philadelphia, PA.

Hall S 1995. Basic biomechanics, 2nd edition. Mosby, St Louis.

Herlin AH and Drevemo S 1997. Investigating locomotion of dairy cows by use of high speed cinematography. Equine Veterinary Journal Supplement 23, 106–109.

Hernandez JA, Garbarino EJ, Shearer JK, Risco CA and Thatcher WW 2005. Comparison of the calving-to-conception interval in dairy cows with different degrees of lameness during the prebreeding postpartum period. Journal of American Veterinary Medical Association 227, 1284–1291.

Hernandez-Mendo O, von Keyserlingk MAG, Veira DM and Weary DM 2007. Effects of pasture on lameness in dairy cows. Journal of Dairy Science 90, 1209–1214.

Hollenbeck AR 1978. Problems of reliability in observational research. In Observing behaviour, vol. II. Data collection and analysis methods (ed. GP Sackett), pp. 79–98. University Park Press, Baltimore.

Holzhauer M, Bartels CJM, van den Borne BHP and van Schaik G 2006. Intra-class correlation attributable to claw trimmers scoring common hind-claw disorders in Dutch dairy herds. Preventive Veterinary Medicine 75, 47–55.

Keegan KG, Pai PF, Wilson DA and Smith BK 2001. Signal decomposition method of evaluating head movement to measure induced forelimb lameness in horses trotting on a treadmill. Equine Veterinary Journal 33, 446–451.

Kestin SC, Knowles TG, Tinch AE and Gregory NG 1992. Prevalence of leg weakness in broiler chickens and its relationship with genotype. The Veterinary Record 131, 190–194.

Main DCJ, Clegg J, Spatz A and Green LE 2000. Repeatability of a lameness scoring system for finishing pigs. The Veterinary Record 147, 574–576.

Manson FJ 1986. A study of lameness in dairy cows with reference to nutrition and hoof care. PhD, The University of Glasgow.

Manson FJ and Leaver JD 1988. The influence of concentrate amount on locomotion and clinical lameness in dairy cattle. Animal Production 47, 185–190.

March S, Brinkmann J and Winckler C 2007. Effect of training on the inter-observer reliability of lameness scoring in dairy cattle. Animal Welfare 16, 131–133.

Martin P and Bateson P 1998. Measuring behaviour: an introductory guide, 2nd edition. Cambridge University Press, Cambridge.

Merkens HW, Schamhardt HC, Hartman W and Kersjes AW 1985. Ground reaction forces of Dutch Warm blood horses at normal walk. Equine Veterinary Journal 18, 207–214.

Morris TR 1999. Experimental design and analysis in animal sciences. CABI Publishing, Oxon, UK.

Morrow DA 1966. Laminitis in cattle. Veterinary Medicine, Small Animal Clinician 61, 138–146.

Neveux S 2005. Hoof pain changes how dairy cattle change their body weight. MSc, The University of British Columbia.

https://doi.org/10.1017/S1751731108003194 Published online by Cambridge University Press

Neveux S, Weary DM, Rushen J, von Keyserlingk MAG and de Passillé AM 2006. Hoof discomfort changes how dairy cattle distribute their body weight. Journal of Dairy Science 89, 2503–2509.

Nikkhah A, Plazier JC, Einarson MS, Berry RJ, Scott SL and Kennedy AD 2005. Infrared thermography and visual examination of hooves of dairy cows in two stages of lactaction. Journal of Dairy Science 88, 2749–2753.

O'Callaghan K 2002. Lameness and associated pain in cattle – challenging traditional perspectives. In Practice 24, 214–219.

Pastell ME and Kujala M 2007. A probabilistic neural network model for lameness detection. Journal of Dairy Science 90, 2283–2292.

Peham C, Licka T, Girtler D and Scheidl M 2001. Hindlimb lameness: clinical judgement versus computerised symmetry measurement. The Veterinary Record 148, 750–752.

Peloso JG, Stick JA, Soutas-Little RW, Caron JC, DeCamp CE and Leach DH 1993. Computer-assisted three-dimensional gait analysis of amphotericin-induced carpal lameness in horses. American Journal of Veterinary Research 54, 1535–1543.

Phillips CJC and Morris ID 2001. The locomotion of dairy cows on floor surfaces with different frictional properties. Journal of Dairy Science 84, 623–628.

Pierrynowski MR and Galea V 2001. Enhancing the ability of gait analyses to differentiate between groups: scaling gait data to body size. Gait and Posture 13, 193–201.

Platz S, Ahrens F, Bahrs E, Nüske S and Erhard MH 2007. Association between floor type and behaviour, skin lesions, and claw dimensions in group-housed fattening bulls. Preventive Veterinary Medicine 80, 209–221.

Rajkondawar PG, Erez B, Neerchal NK, Lefcourt AM, Dyer RM, Varner MA and Tasch U 2002. The development of an objective lameness scoring system for dairy herds – pilot study. Proceedings of the 12th International Symposium on Lameness in Ruminants, Orlando, USA, pp. 411–414. .

Rajkondawar PG, Liu M, Dyer RM, Neerchal NK, Tasch U, Lefcourt AM, Erez B and Varner MA 2006. Comparison of models to identify lame cows based on gait and lesion scores, and limb movement variables. Journal of Dairy Science 89, 4267–4275.

Roepstorff L and Drevemo S 1993. Concept of a force-measuring horseshoe. Acta Anatomica 146, 114–119.

Rushen J, Pombourcq E and de Passillé AM 2007. Validation of two measures of lameness in dairy cows. Applied Animal Behaviour Science 106, 173–177.

Schamhardt HC, van den Bogert AJ and Hartman W 1993. Measurement techniques in animal locomotion analysis. Acta Anatomica 146, 123–129.

Scott GB 1988. Studies of the gait of Friesian heifer cattle. The Veterinary Record 123, 245–248.

Scott J and Huskisson EC 1976. Graphic representation of pain. Pain 2, 175–184.

Smits MCJ, Frankena K, Metz JHM and Noordhuizen JPTM 1992. Prevalence of digital disorders in zero-grazing dairy cows. Livestock Production Science 32, 231–244.

Somers JGCJ, Frankena K, Noordhuizen-Stassen EN and Metz JHM 2003. Prevalence of claw disorders in Dutch dairy cows exposed to several floor systems. Journal of Dairy Science 86, 2082–2093.

Somers JGCJ, Frankena K, Noordhuizen-Stassen EN and Metz JHM 2005. Risk factors for interdigital dermatitis and heel erosion in dairy cows kept in cubicle housing in The Netherlands. Preventive Veterinary Medicine 71, 23–34.

Sprecher DJ, Hostetler DE and Kaneene JB 1997. A lameness scoring system that uses posture and gait to predict dairy cattle reproductive performance. Theriogenology 47, 1179–1187.

Telezhenko E and Bergsten C 2005. Influence of floor type on the locomotion of dairy cows. Applied Animal Behaviour Science 93, 183–197.

van Eerdenburg FJ, de Boer H and Gomez F 2003. Relationship among subclinical lameness and oestrus expression. Proceedings of the 11th International Congress of the International Society of Animal Hygiene, Mexico City, pp. 211–216. .

Van der Tol PPJ, Metz JHM, Noordhuizen-Stassen EN, Back W, Braam CR and Weijs WA 2002. The pressure distribution under the bovine claw during square standing on a flat substrate. Journal of Dairy Science 85, 1476–1481.

Van Weeren PR, van den Bogert AJ and Barneveld A 1988. Quantification of skin displacement near the carpal, tarsal and fetlock joints of the walking horse. Equine Veterinary Journal 20, 203–208.

Vokey FJ, Guard CL, Erb HN and Galton DM 2001. Effects of alley and stall surfaces on indices of claw and leg health in dairy cattle housed in a free-stall barn. Journal of Dairy Science 84, 2686–2699.

Wells SJ, Garber LP and Wagner BA 1999. Papillomatous digital dermatitis and associated risk factors in US dairy herds. Preventive Veterinary Medicine 38, 11–24.

Welsh EM, Gettinby G and Nolan AM 1993. Comparison of a visual analogue scale and a numerical rating scale for assessment of lameness, using sheep as a model. American Journal of Veterinary Research 54, 976–983.

Whay HR 2002. Locomotion scoring and lameness detection in dairy cattle. In Practice 24, 444–449.

Whay HR, Waterman AE and Webster AJF 1997. Associations between locomotion, claw lesions and nociceptive threshold in dairy heifers during the peri-partum period. Veterinary Journal 154, 155–161.

Whay HR, Waterman AE, Webster AJF and O'Brien JK 1998. The influence of lesion type on the duration of hyperalgesia associated with hindlimb lameness in dairy cattle. Veterinary Journal 156, 23–29.

Whay HR, Main DCJ, Green LE and Webster AJF 2003. Assessment of the welfare of dairy cattle using animal-based measurements: direct observations and investigation of farm records. The Veterinary Record 153, 197–202.

Winckler C and Willen S 2001. The reliability and repeatability of a lameness scoring system for use as an indicator of welfare in dairy cattle. Acta Agriculturae Scandinavica A (Supplement) 30, 103–107.

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