Associations between locomotion score and kinematic measures in dairy cows with varying hoof lesion types

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ABSTRACT

During this study we explored the gait attributes commonly used in subjective locomotion scoring systems and use new technology to evaluate these gait attributes objectively on 60 Holstein lactating dairy cattle. Kinematic gait analysis more commonly used in sports and equine science was adapted for use on dairy cattle to assess stride characteristics, joint flexion, and spine posture in dairy cows with different lameness status. Cows that were lame had shorter stride length and had negative tracking distance compared with non-lame cattle. Lame cattle did not show any difference in spine posture when walking. Gait alterations were more evident in cows with sole ulcers, which showed considerable shortening of stride and had more negative tracking compared with cows with no hoof lesions. Cows with sole ulcers also showed significant shortening of the spine when walking than cows with no hoof lesions.

Key words: kinematic, dairy cow, gait, foot lesion

INTRODUCTION

Hoof lesions affect the gait of dairy cattle in different ways. Most animals (72%) have at least 1 foot lesion; however, only 5% of hoof lesions were shown to cause lameness (Manske et al., 2002). Traditionally, locomotion scoring has been used to identify cows with lesions that would benefit from functional trimming. However, locomotion scoring is subjective, with interobserver reliability ranging from, for example, 0.30 (O'Callaghan et al., 2003) to 0.84 (Manson and Leaver, 1988). A reliable method of detecting painful foot lesions (which can reduce the welfare of the affected animals) is needed, as herd sizes are increasing and the availability of skilled staff is becoming more difficult to achieve. Automated means of health monitoring may become more important, particularly for lameness detection.

Automated lameness detection has the potential to detect lameness earlier than the human eye. Cows are stoic prey animals and, as such, may disguise pain. Indeed, they can have lesions without changes in locomotion; however, there are changes in pain thresholds of 30% before gait alterations are seen (Dyer et al. 2007). Also, cows that are classified as sound from locomotion score can have painful claws (Dyer et al. 2007). Several methods have been assessed for automatic lameness detection. The distribution of weight across the 4 legs in a milking robot was used to detect lameness. A model was developed that could correctly classify 96.2% of cows as lame or nonlame (Pastell and Kujala, 2007). Similarly, Chapinal et al. (2010) also assessed weight distribution and shifting as a method of detecting lameness. Rajkondawar et al. (2006) used ground reaction force to identify lame cattle automatically; this has since had adjustments made (Liu et al. 2009) and the system is commercially available as the StepMetric system (BouMatic, Madison, WI). These systems are based on measures of weight and force rather than visual aspects and, therefore, do not take into account such factors as joint flexion and spine posture.

Using visual gait assessments, Flower et al. (2005) have demonstrated specific stride changes in cows with sole ulcers (SU) compared with cows with no lesions. These cows walked more slowly and had shorter strides and longer stride duration than unaffected cows (Flower et al., 2005). Considerable advances have been made in visual technology with markerless technology unitized in new computer game systems. This technology could, therefore, be used to assess gait in cattle with the aim to develop lameness-detection systems; however, this cannot be done until the quantification of the gait of lame and nonlame cattle is undertaken. To date, few works have been published on the effects of specific foot lesions on gait characteristics of dairy cattle. This study will, therefore, address both previously measured gait characteristics as well as those not previously measured on cattle, which have been demonstrated to be significant in equines in relation to lameness. The present study aims to assess these aforementioned gait characteristics in addition to assessing joint motion and flexibility and attempts to quantify back arch and its relationship to different hoof lesions.

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MATERIALS AND METHODS

Animals and Housing

This trial was conducted between March 16 and 30, 2007, at Langhill Farm (Edinburgh, UK). Cows were selected from the herd of 220 cows with an average milk yield of 9,300 L per lactation.

Sixty-five pedigree Holstein lactating dairy cattle were recruited for the study [18 primiparous and 47 multiparous; parity 1–3; mean parity ($\pm$ SE): 2.1 ($\pm$ 0.1)]. Cows at the start of the study were 154 ± 14.3 DIM, giving an average of 34.1 ± 1.4 L of milk per day. Mean withers height was 1.45 ± 0.6 m and the mean length of the back [distance between the thoracic vertebra 3 (**T3**) and tail head (**TA**)] was 1.35 ± 0.8 m.

The cows were group housed in comfort cubicles (ST13 8LB; IAE Ltd., Leek, UK), which had mattresses and were bedded with sawdust 3 times weekly. The floor of the cubicle yards were solid grooved concrete throughout. The collecting yard and walkways were slatted concrete. Cows were housed for the winter period (2006) and were turned out to pasture during the summer months on May 1, 2007.

Cows were fed a TMR, which consisted of grass silage, whole-crop wheat, concentrate, wheat, and molasses. Total mixed ration was fed to support maintenance, plus 28 L of milk with an additional 0.35 kg of concentrate per liter of milk above 28 L, up to a maximum of 6 kg per day, fed in the parlor. The TMR was fed once daily in troughs, which were cleaned out daily before fresh feed was offered. Cows were milked twice daily through a DeLaval 28/28 milking parlor (DeLaval Ltd., St. Mellons, Cardiff, UK), with automatic cluster removal and automatic cow identification.

Cows were grouped for locomotion score 1 (**LS-1**; $n = 20$), 2 (**LS-2**; $n = 20$), or 3 (**LS-3**; $n = 20$) using the method of Flower et al. (2006). Cows were scored by an experienced observer (N. Blackie) with 2 yr of experience. The cows were locomotion scored on a concrete surface while leaving the milking parlor following afternoon milking. No cows scoring 4 or 5 were used in the experiment, as there were not enough cows and

there was no value in using these cows, as we were more interested in the changes in gait that happen before a cow becomes severely lame. The cows were selected to give balanced groups with similar parity profiles and no difference in stage of lactation. Cows were also grouped into parity 1 ($n = 18$), parity 2 ($n = 22$), and parity 3 ($n = 20$). The distribution of cows across the groups is shown in Table 1.

Data Collection for Gait Analysis

Animals were filmed walking along an alley (1.6 m wide) constructed from traffic cones and electric fence posts with a heavy-duty plastic chain connecting the cones. The study was conducted in the collecting yard adjacent to the milking parlor on a strip of solid grooved concrete that ran the length of the yard and was around 2 m wide. The grooved concrete surface the animals were walking on was cleaned before filming began. A digital video camera (Canon PAL MV690; Canon UK Ltd., Borehamwood, UK) was placed 7 m perpendicular to the alley and the field of view captured using the video camera was 4.5 m. Filming took place following morning milking between 0800 and 1500 h. Yellow cardboard markers 3 cm in diameter were glued to the center of rotation of fore and hind limbs of cows using Evo-Stik 528 contact adhesive (Bostik Ltd., Leicester, UK); the location of the markers are given in detail in Table 2. Markers were attached to fore and hind legs to ascertain any differences between fore and hind stride characteristics. Leg markers were attached to the right side of the cow only. In addition to leg markers, spherical orange table tennis balls (4-cm diameter) were attached to the skin over the spinous processes T3, thoracic vertebra 7 (**T7**), lumbar vertebra 1 (**L1**), lumbar vertebra 4 (**L4**), the cranial end of the sacral vertebrae (**SA**) and on the TA. Each cow was then individually guided along the alley by the same handler following the cow at a distance; care was taken to make sure the cow walked at her natural pace (i.e., not rushed) passing the camera 3 to 4 times (minimum of 3). One stride from each run was analyzed. The distance from the elbow marker to the fore fetlock marker was measured manually on the cow to calibrate the distances measured using Simi motion analysis software (a 2-dimensional motion analysis computer program; <http://www.simi.com>; Simi Reality Motion Systems GmbH, Unterschleißheim, Germany).

The films were downloaded using Microsoft Movie Maker (Microsoft Corp., Redmond, WA); film was cut into individual runs and each file was saved in digital video-audio video interleave (DV-AVI) quality for analysis. The images were digitized using Simi motion analysis software. Analyses of the images were then

Table 1. Distribution of cows across parity and locomotion score (LS) groups

LS group ¹	Parity		
	1	2	3
LS-1	8	7	5
LS-2	7	7	6
LS-3	3	8	9

¹Cows were grouped into locomotion score categories using the method of Flower et al. (2006).

Table 2. Description of leg marker placements for gait analysis¹

Marker name	Limb	Location
Fore coffin	Fore	On the coronary band close to the center of rotation of the coffin joint
Fore fetlock	Fore	On the condyle on the distal end of the metacarpal bone at the same height as the sesamoid bone
Knee	Fore	On the center of the carpus between the lateral splint bone and the pisiform bone
Elbow	Fore	2 cm above the lateral tuberosity of the radius
Hind coffin	Hind	On the coronary band close to the center of rotation of the coffin joint
Hind fetlock	Hind	On the condyle on the distal end of the carpal bone at the same height as the sesamoid bone
Hock	Hind	On the flat spot on the talus
Stifle	Hind	2 cm above the head of the fibula

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undertaken using Simi motion analysis as described in the following paragraphs.

Stride length was determined as the distance between the cannon appearing straight and the next occurrence of the cannon being straight for the fore and hind limbs. To calculate this distance, the fetlock marker was highlighted when the cannon was straight and then the film continued until the cannon was straight again and the fetlock marker was selected, which was converted to a distance by the software. Tracking distance was calculated as the distance between the fore foot being placed on the ground (selecting the fetlock marker) and the ipsilateral hind foot being placed on the ground (again, selecting the fetlock marker). A cow with perfect foot placement (where the hind foot is placed where the fore foot had been) would have a tracking value of 0 cm. A negative result indicated that the hind foot failed to reach the placement of the fore foot and, therefore, the cow was short striding.

Hock flexion was assessed by tracking the hind fetlock marker, hock marker, and the stifle marker. The angle between the 3 markers was then calculated by Simi motion analysis. Minimum and maximum angles were calculated and the difference between the 2 gave the joint range of motion (**ROM**). Hind fetlock flexion was assessed by tracking the hind coffin, hind fetlock, and hock joints. Angles were then plotted against percentage of stride and normalized to start at the point at which the cannon appeared straight and the next occurrence of the cannon appearing straight. This normalization allows different animals to be compared directly.

Maximum fetlock height was assessed in still mode of Simi motion analysis and was the highest distance from the floor to the fetlock marker that was seen during the stride. Maximum hock height was measured in a similar way (i.e., the distance between the hock marker and the floor).

The height of each spine marker was assessed when the cow was seen to be bearing weight on the front right foot; the distance from the markers to the floor

was then measured. The length of the spine (T3 to TA), the thoracic (T3 to L1), and lumbar (L1 to SA) regions of the spine were measured from the same frame as above.

Head position was measured when the front right foot was first observed to bear weight; the distance from the bottom of the cow's nose to the floor was also measured using Simi motion analysis. Withers height was measured while the cows were restrained in AI stalls using a height stick. Withers height was measured when the cows were standing square with the head elevated. Back length was measured from the withers to the TA when the cow was restrained in the AI stalls; back length was measured when the cow was standing evenly on all 4 feet. Hoof speed was calculated by dividing the stride length by stride duration.

Foot Lesion Assessment and Locomotion Score Measurement

All hind feet of the cows were assessed for lesions by 1 of 2 trained observers on 1 d within 2 wk after gait analysis. Lesion type and severity were recorded. Two observers were used, as all cows in the herd were hoof trimmed by 3 professional trimmers to ensure that no cows were missed. All hind feet of the cows were trimmed; only front feet with abnormal shape were trimmed. The severity of each lesion was scored using the method of Flower et al. (2005). All cows were locomotion scored using the method for scoring walking cows of Flower et al. (2006) before gait analysis. Cows were then selected for the study on the basis of locomotion score; groups were then balanced for parity and stage of lactation.

The most prevalent lesion was sole hemorrhage (**SH**; 43%), followed by digital dermatitis (**DD**; 19%), heel horn erosion (**HE**; 15%), SU (10%), and white line separation (6%). All gait attributes were measured on the right side of the animal; the effect of lesion on stride characteristics was assessed on the back right foot. Where cows had more than 1 lesion, the most

severe lesion (highest severity score, or SU) was used to group the cows. If the cow had a lesion on the left only, it was excluded from analysis; however, cows with a less severe lesion on the left were included (i.e., most severe lesion on the right side). Therefore, cows were grouped into 5 groups based on hoof lesions; these were no lesions (none), SU, SH, DD, and HE.

Data Analysis

All differences among cows of different locomotion score were tested for skewness using Pearson's test and were found to be normally distributed, with the exception of tracking distance. Stride data (fore stride length, hind stride length, stride duration, fetlock height, hock height, hock ROM, hock minimum angle, hock maximum angle, fetlock ROM, fetlock minimum angle, and fetlock maximum angle) conformation data (withers height, back length, and calibration length) and spine posture data (spine length, standing; spine length, walking; thoracic spine length; lumbar spine length; and spine length difference) were tested using ANOVA against locomotion score category (LS-1, LS-2, and LS-3). A separate ANOVA was performed on the same variables noted above against hoof lesion type (none, SU, SH, DD, and HE). Multiple comparisons were made using the post-hoc Tukey test ($P < 0.05$). The tracking distance data were tested the using the Kruskal-Wallis test. All data were analyzed using GenStat (version 8; VSN International Ltd., Hemel Hempstead, UK). Variables were calculated as the average of 3 runs, with each cow acting as one experimental unit.

Sixty-five cows were present for the gait analysis experiment; 2 cows were culled for management reasons before lesion assessment and 1 cow was not presented

for foot lesion assessment due to developing toxic mastitis; therefore, foot lesion data was available for 62 cows and only these cows were included in the analysis. Two further cows did not have useable videos for gait analysis, as the cows did not perform a normal walking gait (galloped, stopped, or bucked) for all of the runs; these 2 cows were also removed from analysis. Therefore, data from the 60 remaining cows were analyzed.

RESULTS

The stride characteristics of the cows were different according to locomotion score (Table 3). Cows had shorter stride lengths with increasing locomotion score. Cows with LS-3 had significantly shorter ($F_{2,57} = 4.33$; $P = 0.018$) fore stride length than cows with locomotion score 1 (1.54 vs. 1.71 m, respectively). A similar pattern was seen for the hind stride: locomotion score 3 cows had significantly shorter ($F_{2,57} = 3.66$; $P = 0.032$) stride length than LS-1 cows.

The LS-3 cows had a shorter tacking distance than LS-1 cows (-0.03 vs. 0.02 m, respectively); however, this did not reach significance. A weak tendency was also observed for LS-3 cows to have longer stride duration than LS-1 and LS-2 cows (Table 3). No difference was observed across locomotion score groups for maximum hock and hind fetlock height. The cows in the present study showed differences in stature across the locomotion score groups; the LS-2 and LS-3 cows had significantly different withers height and LS-3 cows were 3 cm taller at the withers than LS-2 cows.

Limited effect was observed of locomotion score on the ROM of joints (Figure 4). The ROM gives an idea of the flexion of the joint. A tendency was observed for locomotion score to affect maximum hock angle;

Table 3. Stride characteristics, conformation, parity, and stage of lactation of cows with different locomotion scores¹

Item	Locomotion score 1 (n = 20)	Locomotion score 2 (n = 20)	Locomotion score 3 (n = 20)	SEM	Significance (<i>P</i> -value)
Fore stride length (m)	1.71 ^a	1.64 ^{ab}	1.54 ^b	0.039	0.02
Hind stride length (m)	1.69 ^a	1.64 ^{ab}	1.54 ^b	0.042	0.03
Tracking distance ² (m)	0.02	-0.02	-0.03	0.014	0.06
Stride duration (s)	1.12	1.09	1.31	0.079	0.11
Maximum hind fetlock height difference (m)	0.09	0.08	0.07	0.030	0.23
Maximum hock height difference(m)	0.09	0.08	0.08	0.040	0.69
Withers height (cm)	145 ^{ab}	144 ^a	147 ^b	0.956	0.05
Back length (cm)	134	135	136	1.409	0.45
Calibration length (cm)	65	65	65	0.564	0.82
Parity	1.85	1.95	2.30	0.177	0.18
DIM	162	146	155	25.1	0.90

^{a,b}Different superscripts indicate significant differences between means within rows ($P < 0.05$).

¹Locomotion scores were assigned based on the method of Flower et al. (2006).

²Analyzed using the Kruskal-Wallis test as nonparametric data. All other data analyzed using ANOVA with post-hoc Tukey tests.

Table 4. Hind limb joint angles and range of movement (ROM) of the joints of cows with different locomotion scores¹

Item	Locomotion score 1 (n = 20)	Locomotion score 2 (n = 20)	Locomotion score 3 (n = 20)	SEM	Significance (<i>P</i> -value)
Hock ROM (degree)	27.3	28.6	27.0	4.59	0.53
Hock, minimum (degree)	136.5	138.2	140.1	6.71	0.26
Hock, maximum (degree)	163.8	166.8	167.1	4.68	0.06
Fetlock ROM (degree)	57.5	57.9	55.9	12.86	0.88
Fetlock, minimum (degree)	155.8	156.5	157.3	10.08	0.89
Fetlock, maximum (degree)	213.2	214.4	213.3	13.51	0.95

¹Locomotion scores were assigned based on the method of Flower et al. (2006).

this may indicate that the animals were less flexible; however, differences were very small.

No effects were observed of locomotion score on the marker height (Figure 1). The LS-3 cows had numerically higher spine markers on T3, T7, L1, and L4.

Spine length was assessed while the animal was standing square (spine length, standing) and it was then measured when the cows were walking. The difference between these measurements gives an indication of the changes in the spine posture when the cow walks (Table 5). No effect was observed of locomotion score on the spine length overall, in the lumbar or thoracic regions (Table 5).

Differences were observed in fore stride length variation between runs; LS-1 cows had significantly higher ($F_{2,57} = 4.60$; $P = 0.014$) variation (0.17 vs. 0.08, respectively) than LS-2 cows; LS-3 cows were intermediate ($SD = 0.10$) and not different from LS-1 or LS-2 cows. A similar effect was found of locomotion score on hind

stride length variation between runs; LS-1 cows had significantly greater variation ($F_{2,57} = 3.67$; $P = 0.032$) than LS-2 cows (0.17 vs. 0.10, respectively). Again, LS-3 cows were intermediate ($SD = 0.13$). Tracking length variation increased numerically with locomotion score, although this was not statistically significant (0.03, 0.04, and 0.05 for LS-1, LS-2, and LS-3, respectively).

Stride length was 27 cm shorter ($F_{4,47} = 2.87$; $P = 0.033$) in cows with SU compared with cows with no lesions or any other hoof lesions (Table 6). A tendency existed for cows with SU to have a shorter tracking distance than cows with no lesions. The mean head position was similar for cows with SU to those with no lesions or any other lesions. Cows with SU had significantly higher locomotion score (2.86) than cows with no lesions ($F_{4,47} = 3.36$; $P = 0.017$). This means that 6 of the 7 of the cows suffering from SU (86%) were scored as lame (LS-3). However, 3 of the cows (23%) with no detected lesions were scored as LS-3. Cows

Figure 1. Spine marker height for cows with different locomotion scores. No significant differences were found between points. T3 and T7 = thoracic vertebrae 3 and 7, respectively; L1 and L4 = lumbar vertebrae 1 and 4, respectively; SA = sacral vertebrae; TA = tail head. Locomotion scores were assigned based on the method of Flower et al. (2006).

Table 5. Spine length across locomotion scores 1, 2, and 3¹

Item	Locomotion score 1 (n = 20)	Locomotion score 2 (n = 20)	Locomotion score 3 (n = 20)	SEM	Significance (<i>P</i> -value)
Spine length, standing (m)	1.34	1.35	1.36	0.06	0.45
Spine length, walking (m)	1.32	1.34	1.34	0.07	0.75
Thoracic spine length (m)	0.46	0.47	0.47	0.05	0.57
Lumbar spine length (m)	0.53	0.53	0.54	0.07	0.81
Spine length difference (m)	-0.02	-0.01	-0.03	0.06	0.64

¹Locomotion scores were assigned based on the method of Flower et al. (2006).

with SH had higher locomotion scores than cows with DD, HE, and no lesions.

No effect was observed of hoof lesions on the joint ROM in both the hind fetlock and hock (Table 7). Cows suffering from SU had similar ROM in the fetlock compared with cows with no lesions and those with different types of lesions.

No relationship was determined between hoof lesions and the height of the spine markers (Figure 2). The heights of the spine markers in cows with SU were numerically lower at the TA than cows with no lesions or other lesions.

The spine length was measured when the cows were standing and then when they were walking. No significant difference was observed in spine length (walking) in relation to lesion type. This measurement does not take into account the different individual measurements of the cows when measured standing; however, no statistical differences were observed in back length (standing) in relation to lesion group (Table 8). Spine length difference was calculated as the difference between the cows standing and walking in terms of back length. In the case of cows with SH, back length actually increased when walking, which may indicate that these cows were dipping the spine, although this effect was very small. A significant difference ($F_{4,47} = 3.11$; P

$= 0.024$) was noted between cows with SU and those with SH; the cows with ulcers shortened the back by an average of 8 cm when walking; this may indicate that they were arching the spine even though no difference existed in the marker height in the center of the spine (L1). One limitation of this measurement was that it did not assess any arching of the spine when the animal was standing square.

DISCUSSION

Small but significant changes occurred in the gait of dairy cattle with increased locomotion score and also with different hoof lesions. Greater effects of painful lesions (SU) were observed on the gait characteristics of dairy cows. This is consistent with cattle being prey animals, which are stoic and, therefore, they are less likely to show behavioral responses to pain until the injuries are more severe (Weary et al., 2006).

Video Analysis of Gait and Its Applications

This work has demonstrated an association between locomotion score, hoof lesions, and kinematic gait analysis undertaken using video. This is promising for automated lameness assessments, as the video technol-

Table 6. Effect of type of lesion on stride characteristics, production, and head position of dairy cattle¹

Item	None (n = 13)	SU (n = 70)	SH (n = 19)	DD (n = 8)	HE (n = 5)	SEM	Significance (<i>P</i> -value)
Stride length (m)	1.71 ^a	1.44 ^b	1.67 ^a	1.58 ^a	1.54 ^a	0.190	0.03
Tracking ² (m)	0.00	-0.08	-0.02	-0.02	0.02	0.065	0.09
Stride duration (s)	1.18	1.18	1.23	1.10	1.22	0.396	0.95
Hoof speed (m/s)	1.69	1.26	1.56	1.54	1.38	0.651	0.68
Head position (m)	0.76	0.69	0.74	0.73	0.73	0.094	0.69
Locomotion score	1.77 ^a	2.86 ^b	2.11 ^{ab}	1.75 ^a	1.60 ^a	0.739	0.02
Maximum fetlock height difference (m)	0.08 ^{ab}	0.08 ^{ab}	0.08 ^{ab}	0.07 ^a	0.12 ^b	0.027	0.04
Maximum hock height difference (m)	0.07 ^{ab}	0.08 ^{ac}	0.09 ^b	0.09 ^b	0.14 ^b	0.035	0.006
Withers height (cm)	1.45	1.48	1.46	1.44	1.45	0.045	0.57
Back length (cm)	1.35	1.40	1.33	1.36	1.35	0.062	0.11
Parity	2.0	2.0	1.9	2.3	2.2	0.83	0.86

^{a-c}Different superscripts indicate significant differences between means within rows ($P < 0.05$).

¹None = no lesion; SU = sole ulcer; SH = sole hemorrhage; DD = digital dermatitis; HE = heel horn erosion.

²Analyzed using the Kruskal-Wallis test as nonparametric data. All other data analyzed using ANOVA with post-hoc Tukey tests.

Figure 2. Effect of foot lesion on spine marker height while walking. None = no lesion; SU = sole ulcer; SH = sole hemorrhage; DD = digital dermatitis; HE = heel horn erosion. T3 and T7 = thoracic vertebrae 3 and 7, respectively; L1 and L4 = lumbar vertebrae 1 and 4, respectively; SA = sacral vertebrae; TA = tail head.

ogy available is rapidly developing/evolving and, as such, a markerless method of gait analysis could be produced, thus allowing stride length and tracking to be measured automatically and changes in these variables could detect hoof lesions. Such a system could be incorporated into the race leaving the parlor, particularly as work has demonstrated that gait changes due to SU are more evident following milking (Flower et al., 2006). The cows used in this study ranged in from LS-1 to LS-3 and did not include any severely lame cattle. The value of determining gait attributes in severely lame cows is less than moderately lame cows, particularly as it is relatively easy to identify severely lame cows. Indeed, work has shown that mildly lame cows treated early resulted in cows being less likely to require further treatments and reduced the prevalence of lameness (Leach et al. 2012). Development of automatic lameness detection systems should detect any gait adaptations earlier than the human eye.

Stride length and stride duration were not different between sound and bilateral lameness in the equine (Buchner et al., 1995a,b). Therefore, it may be difficult to assess bilateral lameness in kinematic studies due to

the absence of asymmetry in gait. This warrants more investigation in cattle.

Relationship Between Locomotion Score and Kinematic Gait Analysis

Differences in stride length variation were consistent with those seen in equines. Peham et al. (2001) found that horses that were naturally lame in the forelimb had lower stride length variation than the same horses that had nerve blocks (had become sound). Peham et al. (2001) suggested that, in this case, the horses had adopted the optimum compensatory movements to minimize pain. The duration of lameness in the cows in the present study is not known and it is not clear in bovines how long it would take for animals to adopt such compensatory movements. The differences between LS-1 and LS-2 cows could be attributed to differences in gait occurring before the cow becomes more visibly lame (i.e., transition to LS-3). There may be value in further investigation of these results and these differences seen in the LS-2 cows may be particularly useful for lameness prediction purposes.

Table 7. Effect of foot lesions on the range of movement (ROM) of the joints and minimum and maximum joint angles for hock and hind fetlock¹

Item	None (n = 13)	SU (n = 7)	SH (n = 19)	DD (n = 8)	HE (n = 5)	SEM	Significance (<i>P</i> -value)
Hock ROM	27.6	27.0	26.5	29.6	30.2	4.72	0.41
Hock, minimum	137.4	137.6	139.4	137.7	135.8	7.00	0.84
Hock, maximum	165.0	164.6	165.9	167.3	165.9	5.09	0.86
Fetlock ROM	58.5	49.4	55.8	62.5	61.8	12.77	0.30
Fetlock, minimum	156.6	158.6	156.4	157.7	150.4	10.21	0.71
Fetlock, maximum	215.1	207.9	212.2	220.2	212.2	13.94	0.51

¹None = no lesion; SU = sole ulcer; SH = sole hemorrhage; DD = digital dermatitis; HE = heel horn erosion.

Table 8. Effect of hoof lesion on spine length¹

Item	None (n = 13)	SU (n = 7)	SH (n = 19)	DD (n = 8)	HE (n = 5)	SEM	Significance (<i>P</i> -value)
Spine length, walking (m)	1.33	1.32	1.33	1.34	1.34	0.08	0.99
Thoracic spine length (m)	0.46	0.49	0.46	0.48	0.44	0.05	0.46
Lumbar spine length (m)	0.53	0.50	0.53	0.55	0.58	0.07	0.42
Spine length difference (m)	-0.02 ^{ab}	-0.08 ^a	0.01 ^b	-0.02 ^{ab}	0.00 ^{ab}	0.03	0.02

^{a,b}Different superscripts indicate significant differences between means within rows ($P < 0.05$).

¹None = no lesion; SU = sole ulcer; SH = sole hemorrhage; DD = digital dermatitis; HE = heel horn erosion.

The height of spine markers was not different for cows with locomotion scores 1 to 3. Shortening of the lumbar and thoracic regions was assessed separately, as well as the length of the back from T3 to SA for cows with locomotion scores 1 to 3, which were again found to be similar across locomotion score groups. It is possible that the marker height was not sensitive enough to use to measure back arch; it would be expected that arching the back would result in the markers being higher in the middle of the spine for lame cows. However when the spine posture is plotted (Figure 1), it is possible to visualize spine shape differences between the 3 groups, with the LS-1 cows having a flatter back posture.

When the cows were grouped according to locomotion score, little difference was seen in many of the specific gait attributes assessed, except in stride attributes (length and timing). This may highlight benefits of using locomotion scoring to assess cattle for hoof lesions; however, in the present study, most of the cows suffering from painful sole lesions (SU) were scored as lame (LS-3). Some caution should be used in interpreting these results, as LS-3 cows were slightly older and taller; this may have reduced apparent differences, as taller cows would have longer strides (parity and withers height were not significantly different between locomotion score groups).

The decreased stride length and negative tracking with increasing locomotion score seen in the present study are supported by work performed on horses and cattle. Work in horses demonstrated that subtle lameness had no effect on stride length at walk (Buchner et al., 1996; Gomez Alvarez et al., 2008) or trot (Gomez Alvarez et al., 2008), as also demonstrated in dairy cows by Telezhenko and Bergsten (2005) and confirmed by the current study. More severe lameness causes (e.g., SU does seem to affect stride length more; Flower et al. 2005).

Effect of Specific Hoof Lesions on Gait Attributes

Cows with sole lesions showed the most compensatory gait attributes compared with cows that had no sole lesions. The stride length on the lame foot was

significantly shorter in cows with SU compared with no lesions, with a difference of 27 cm; these changes are in agreement with those reported by Flower et al. (2005), who found that cows with SU had significantly shorter stride length. Sole hemorrhage had less effect on gait attributes, with cows having similar stride lengths to cows with no lesions. Flower et al. (2005) found no difference between cows with no lesions and those with sole lesions (hemorrhage). A similar effect on stride length was seen in cows with DD and HE.

In the present study, hoof speed was less for cows with SU compared with for those with no lesions. Flower et al. (2005) also showed that cows with SU moved significantly more slowly than those with healthy feet. The cows with SU did not lift the hoof as high as those cows with no lesions; however, they did have a similar stride duration, which may be explained by the slower hoof speed. Cows with SH had the longest stride duration of the lesion groups and had lower hoof speed than cows with no lesions. In agreement with the present study, Flower et al. (2005) found that cows with sole lesions had longer stride duration and lower hoof speed than those with no lesions (these effects were again not significant). The speed and stride duration differences may indicate more careful foot placement compared with cows with no hoof lesions. Cows with DD had similar fetlock height to cows with no lesions, SU, and SH, but fetlock height was significantly ($P = 0.04$) lower than cows with HE. Hock height was not different for cows with DD and no lesions or SH or HE, but was higher than cows with SU. This may be due to the differences in the etiology of the different lesions; SU may cause more pain when the foot hits the floor, whereas that lesion affecting the heel (DD) may cause pain when the animal's foot leaves the floor or the fetlock is flexed. Maximum fetlock height and hock height was significantly higher for cows with HE compared with cows with DD. This may indicate that the cows were lifting their feet higher, which might suggest they were experiencing pain when the hoof left the floor, which might have caused the skin of the heel to stretch, causing pain to the animal. Similarly no difference existed in hind fetlock and hock height for cows with SH.

Maximum stride height was also similar between cows with sole lesions and no lesions in the study by Flower et al. (2005).

Slight changes were observed in the spine posture of the cows with SU, which may help to explain the compensatory movements of the animal. These cows showed an increase in the length of the thoracic region of the spine, indicating that the animals were showing dorsal flexion in this region, accompanied by a decrease in the length of the lumbar region. These effects combined with an overall shortening of the spine in the cows with SU compared with those with no lesions, but were not accompanied with an increase in spine marker height. These adaptations may be used by the animal to relieve pain from what has been shown to be a painful foot lesion (Whay et al., 1998, 2005).

Tracking was lowest for SU and little effect was observed of other lesions on tracking distance compared with cows with no lesions. One exception was that cows with HE were the only ones to have a positive tracking distance. Head position, hock ROM, and hind fetlock flexion were similar across lesion groups.

CONCLUSIONS

Video gait analysis of cattle has the potential to detect hoof lesions, particularly using stride length and tracking measurements. An interesting finding was the fact that cows with DD and HE lift their feet higher and this warrants further research into why this gait adaptation occurs. Sole ulcers had the most obvious effects on gait and showed marked changes of stride length and had an effect on spine posture, seen by a significant reduction in spine length between standing and walking. Cows that were lame showed significantly less variation in fore and hind stride length, which may indicate that these cows were adopting the best compensatory movements to minimize pain. Stride length, tracking, hoof height, and back length changes have the most potential for inclusion into an automated lameness detection system. Currently, the limitation of this system is the need for markers; however, the development of new technology may mean that the markers will not be required in the future.

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