Evaluation of two methodologies for lameness detection in dairy cows based on postural and gait abnormalities observed during milking and while restrained at headlock stanchions.

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ABSTRACT

Lameness is a critical issue on dairies with an impact on production and animal welfare. Early lameness detection followed by effective treatments could improve prognosis and cure rate of lame cows. Current methods for lameness detection are based on locomotion score (LS) that requires observation of cows walking, preferably at the exit of the milking parlor. This is a time-consuming task that is difficult to implement on large dairies. Therefore, a common methodology for lameness detection is based on milkers' and cow pushers'

observations of cows walking to the milking parlor or standing at the milking stall (MPP). Observation of postural abnormalities predictive of lameness while cows are locked at stanchions (S) can be used as an alternative detection method. The objective of this research was to study the association between postural and gait abnormalities observed with S and MPP methodologies and lameness using $LS \geq 3$ as the reference method, as well as to evaluate the epidemiological characteristics of those methods as a diagnostic test for lameness. A secondary objective was to describe the type of hoof lesions observed with postural and gait abnormalities detected with LS, MPP, and S methodologies. A cross-sectional study design was performed on 2,274 cows from one farm in California (US). Arched back, cow-hocked, wide-stance, and favored-limb postures as well as uneven gait were observed. Both lameness detection methodologies, S and MPP, indicated that arched back and favored-limb were postural abnormalities associated with lameness. However, the epidemiological test characteristics for each of the postures evaluated as a diagnostic test for lameness indicated that both detection methods, S and MPP, had good specificity (> 0.91) but poor sensitivity (0.04 to 0.39). A convenience sample of 104 cows, selected based on $LS > 3$, favored-limb, presence of two or more abnormal postures, and gait anomalies with either S or MPP methods, received a hoof examination. Lesions were observed on cows selected by LS (17/24), MPP (21/30), and S (33/60) criteria, suggesting a lack of concordance between lameness detection methodologies and visible hoof lesions. Nevertheless, due to the lack of acceptance of LS as the lameness detection method on large commercial dairies in California, it is imperative that future research evaluates modifications of S and MPP lameness detection techniques, considering hoof lesion as reference method.

Keywords: lameness detection, locomotion score, hoof lesions

Abbreviations: LS, locomotion score; MPP, lameness detected by milkers while cows stand at the milking parlor and by pushers when cows walk towards the parlor; S, Observation of

51 postural abnormalities predictive of lameness while cows are locked at stanchions; ArchS,
52 arched back posture observed at stanchions; HockS, cow-hocked posture observed at
53 stanchions; FavS favored-limb posture observed at stanchions; Stance S, wide-stance posture
54 detected at stanchions; ArchMPP, arched back posture observed entering the parlor or
55 walking to the milking parlor; HockMPP, cow-hocked posture observed at milking parlor,
56 FavMPP, favored-limb posture observed at or walking to the milking parlor; GaitMPP,
57 uneven gait observed walking to the milking parlor; LACT, lactation number; DIM, days in
58 milk; AVMK, average milk from Day 1 to 7.

1. Introduction

Lameness on dairies is a world-wide problem that negatively impacts animal welfare (Juarez et al., 2003; O’Callaghan et al., 2003; Dyer et al., 2007), herd production level (Sprecher et al., 1997; Juarez et al., 2003; Archer et al., 2010; Huxley, 2013; Norring et al., 2014) and social perception of livestock farming (Leach et al., 2010). Previous research shows a wide variation of lameness prevalence across countries, herds, seasons, and housing types, ranging from 3% to 60% (Espejo et al., 2006; Cramer, 2007; Tadich et al., 2010; Hoffman et al., 2014). Current lameness prevalence in cattle is considered unacceptably high (Potterton et al., 2012).

Lameness prevalence on dairy herds could be reduced by adopting mitigation strategies that decrease lameness incidence, or by early lameness detection and treatment that improves prognosis and cure rate (Leach et al., 2012). However, dairy producers seem to have difficulties with lameness identification resulting in an underestimation of its prevalence (Whay et al., 2003; Espejo et al., 2006). Thus, accurate lameness detection methods that could be easily implemented on dairies will be valuable tools to decrease lameness prevalence.

Automatic systems for lameness detection based on behavior, kinematic, and kinetics approaches have gained attention over the last decade. However, they are still at an early developmental stage and require further development (Bicalho et al., 2007; Viazzi et al., 2013; Schlageter-Tello et al., 2014). Consequently, visual observation of gait and posture abnormalities remains the most common method to identify lame cows. Various scoring methods have been proposed to assess gait. The five-level locomotion score (LS) system described by Sprecher et al. (1997) is widely referred to in the literature. Most research

studies evaluating the efficacy of preventive strategies and treatment of hoof lameness in cattle use LS or gait score as the reference technique (Potterton et al., 2012). However, LS evaluations require individual observation of walking and standing cows, most often when leaving the milking parlor. This is a time-consuming task, difficult to implement on most large dairies. Some studies have proposed new strategies that could be easily implemented on commercial dairies (Leach et al., 2009; Thomsen, 2009; Hoffman et al., 2014). Based on behavior indicators related to abnormal weight distribution, Leach et al. (2009) proposed a method to detect lameness while cows were restrained on tie-stalls. Lameness indicators included weight shifting between hind legs, resting a foot, uneven weight when moving from side to side, and reluctance to bear weight on a particular foot. Thomsen (2009) evaluated arched back posture of cows standing in pens as a diagnostic method for lameness detection. Most recently, Hoffman et al. (2014) evaluated a simple lameness detection method while cows were restrained at self-locking stanchions. Observed postural abnormalities included arched back, cow-hocked, wide-stance, and favored-limb. Overall, these methodologies showed limited validity as diagnostic tests for lameness.

Farm personnel observations of lame cows while walking to the milking parlor (cow pusher) or standing at the milking stall (milkers) are commonly used as the methodology for lameness detection (**MPP**). Prior research on hoof lesion identification at the milking parlor was limited to digital dermatitis (Rodriguez-Lanz et al., 1998; Relun et al., 2011; Stokes et al., 2012). To the best of our knowledge, the present study is the first one assessing the reliability of detection techniques based on postural and gait observations carried out during milking as a lameness diagnostic test. Furthermore, observation of postural and gait abnormalities predictive of lameness while cows are locked at stanchions (**S**) could be used as an alternative detection method. Thus, the objective of this research was to study the association between postural and gait abnormalities observed with S and MPP methodologies

and lameness using $LS \geq 3$ as the reference method, as well as evaluate the sensitivity and specificity of these postural and gait observations, with locomotion scoring as the gold standard. A secondary objective was to describe the type of hoof lesions observed with postural and gait abnormalities detected with LS, MPP, and S methodologies.

2. Materials and methods

All procedures were approved by the University of California Davis Institutional Animal Care and Use Committee (# 17440).

2.1. Cows and herd management

The study was conducted in May 2014 over a ten-day period on a 2,384 lactating Holstein cow free-stall commercial dairy farm in Tulare County (California). There were 13 lactating cow pens on the study dairy. Cows were milked twice a day in two 20 by 20 herringbone parlors and fed a total mixed ration twice a day. Average milk yield was 37.2 kg per cow and day. Stalls were bedded with dry manure and new bedding was added every two weeks. Feed alleys were made of grooved-concrete floors that were flushed twice a day with lagoon water. Walkways to the milking parlor were made of grooved concrete padded with rubber mats. At the exit of the milking parlor, cows walked through a foot bath of 258 cm length and 190 cm width, with 5% of formalin (35 per cent formaldehyde). At dry-off, cows were scheduled to visit the hoof trimmer. Twice a week, before the hoof trimmer visit, on-farm employees identified lame cows during milking.

2.2. Observers training

In this study, the two researchers (AGM & NS) performing field observations were experienced Veterinary Faculty members who have conducted similar studies. In order to minimize intra- and inter-observer disagreement, both observers were intensively trained

prior to study onset. Observers reviewed online materials (WSU Washington State University, Zinpro Corp. 2010) and completed three practice rounds for LS: 200 cows, 1,000 cows, and 1,000 cows. When researchers disagreed on scores, cows were noted and re-evaluated afterwards.

The observation of postural abnormalities while cows were standing in stanchions was carefully evaluated according to methodology described by Hoffman et al. (2014). Researchers did three practice rounds to ensure they agreed on how to score cows standing on stalls. The first practice round was done in a single pen (300 cows). Both researchers observed cows from behind and discussed postures while observing cows' reaction to observers. Photos of questionable postures (especially cow-hocked) were taken and discussed in the lab. Once researchers agreed on their scoring system, they did a practice round scoring 2,000 cows.

Researchers did three scoring practice rounds at the milking parlor. During one round, they were accompanied by a colleague with experience evaluating digital dermatitis in the milking parlor. During the first round, observers focused on finding the best placement inside the milking parlor to detect an arch back. Researchers devoted time and effort to achieve unifying criteria on cow-hocked and favored-limb postures while at the milking parlor pit. Both evaluators walked with the pusher during a single practice round. Once the training phase was completed, the percentage of intra-observer reliability and kappa agreement (Fleiss et al., 2003) was assessed using videos of cows walking, locked in stanchions, and during milking as previously described by Hoffman et al. (2014). Videos were evaluated 14 days apart to calculate intra-observer reliability.

2.3. Study design and data collection

A cross-sectional study was designed to evaluate MPP and S lameness detection methodologies based on postural and gait abnormalities observations using LS as reference

method. On Days 1 and 2, cows were evaluated following the S method for lameness detection. One researcher (AGM) observed cows from behind while locked at stanchions while a second researcher (NS) noted cow ID and double-checked arched back posture on ambiguous cases. Cows were restrained after the morning feeding between 5 to 7 a.m. and before milking, starting at 8 a.m. In six pens, cows were restrained as part of the farm management plan for breeding, tail chalking, or fresh cow checks. In seven other pens, cows were locked just to collect study observations. Each pen ranged in size from 114 to 237 cows and evaluations lasted 30 to 45 minutes per pen.

Observed postural abnormalities included arched back (**ArchS**), cow-hocked (**HockS**), favored-limb (**FavS**), and wide-stance (**StanceS**), as described by Hoffman et al. (2014). All cows showing an obvious upper limb lesion or disease, not locked, pulling back against the head restraint, or too big for stanchions, were excluded from the assessment. Excluding these animals, a total of 2,009 cows were evaluated in headlock stanchions. Only cows urinating or defecating during the first round of observations were rechecked.

On Days 3 and 4 all lactating cows (n = 2,384) in the herd were evaluated by the MPP method observing arched back, cow-hocked, wide-stance, and favored-limb postures. One of the authors (AGM) recorded three postural abnormalities at the milking parlor: arched back (**ArchMPP**) entering the parlor, cow-hocked (**HockMPP**), and favored-limb (**FavMPP**) while standing in the milking stall. Any degree of convexity between the withers and the tail-head was considered an ArchMPP. To detect this posture, cows were observed from the milking pit while freely entering the parlor stalls. Researchers evaluated HockMPP and FavMPP during the milking process. A cow was considered to display favored-limb if she avoided resting weight on a limb or shifted weight between limbs. A cow was classified as cow-hocked if both hocks were turned inward, causing the toes to turn outward. During milking, a second researcher (NS) followed the pusher while bringing cows to the milking

parlor holding area. The researcher had an opportunity to evaluate the gait and abnormal postures from the last group of cows walking towards the parlor. Three postural abnormalities were observed at this time: arched back (**ArchMPP**), uneven gait (**GaitMPP**), and favored-limb (**FavMPP**).

On Days 6 and 7, cows were locomotion-scored as they exited the milking parlor walking through a narrow sort lane. The flat and even walking surface was made of grooved concrete. Scoring was done simultaneously by two trained researchers (AGM and NS), according to the 5-point scale of Sprecher et al. (1997). When evaluators disagreed on scores, cows were noted and re-evaluated afterwards. Briefly, cows with a score 1 stand and walk with a level-back posture and show a normal gait; score 2 is a subtle variation of score 1 and indicates a cow with an arched back posture while walking but not while standing; score 3 indicates a moderately lame cow that shows an arched back posture standing and a gait with short striding; score 4 indicates a lame cow that additionally favors one or more limbs; score 5 includes severely lame cows showing reluctance to bear weight on one or more limbs. For all analyses, cows were classified as lame with an LS of 3 to 5. The final number of cows evaluated for LS was 2,274. A total of 110 cows were not scored as they walked too fast through the sorting lane before researchers had time to evaluate them.

Field data was entered into spreadsheets for data analysis (Microsoft Office Excel 2010). Cow-level information on lactation number (**LACT**) and days in milk (**DIM**) was extracted from the dairy-records database Dairy Comp 305 (Valley Agriculture Software, California). Cow milk yield records were extracted from Afifarm management software (Afimilk Ltd, Israel) to calculate average milk yield from Day 1 to Day 7 (**AVMK**).

On Day 10, all cows favoring a limb or observed with two or more postural deviations detected by S or MPP, or with LS>3 were selected for a hoof evaluation at the trimming table. Cows with upper lesions or treated by the hoof trimmer during the last 2 months were

excluded from the evaluation. A total of 104 cows were evaluated by the dairy hoof trimmers under the supervision of researchers. Lesions were recorded following definitions by ICAR Claw Health Atlas (2015) and scored lesion severity using a modified abc lesion scoring system described by Burghi and Cook (2006). When more than one hoof lesion was detected, the most severe one was classified as the cause of lameness.

2.4. Statistical Analysis

Percentage of inter-observer agreement and kappa statistic (Fleiss et al., 2003) were calculated for LS, S, and MPP methodologies. Kappa statistic was calculated as the relation between the observed agreement not due to chance compared to the maximum non-chance agreement. For variables with more than two categories, weighted kappa was calculated, assigning linear weights to assess agreement (Szklo and Nieto, 2007).

To evaluate the relationship between the reference lameness detection method (LS $\geq$ 3) and postural abnormalities detected with S and MPP methodologies, two logistic regression models were constructed. To identify potential good predictors of lameness, an univariable logistic regression model was built for each of the categorical variables observed with S (ArchS, HockS, FavS, and StanceS) and MPP (ArchMPP, HockMPP, FavMPP, and GaitMPP) lameness detection methodologies. The logistic regression assumption regarding linear relationship with the log odds was assessed for DIM, AVMK and LACT; DIM and AVMK were categorized and only LACT was kept as a continuous variable. Each of these variables was considered potential good predictors, and therefore included in the maximum model, when their 95% confidence interval of the crude odds ratio (**OR**) did not include one. The presence of confounding was assessed comparing the adjusted OR with the crude OR for each variable. If a change of at least 20% between OR was detected, the variable was considered a confounder. After the selection of the maximum model for each methodology,

stepwise procedure was used to select the variables that resulted in a reduction of the Akaike's information criterion (**AIC**). All confounders were forced into their respective models and all two-way interactions between candidate variables were tested and retained if they minimized the value of the AIC. Goodness of fit was assessed with the Hosmer-Lemeshow statistic for each final model (Kleinbaum et al., 2010). The area under the receiver operating characteristics curve (**ROC**) was used to quantify the predictive ability of the model.

Using LS as the reference method, each postural abnormality included in the final regression model and all their possible combinations with S and MPP were evaluated as a diagnostic test for lameness based on sensitivity (**Se**), specificity (**Sp**), positive and negative predictive values (**PPV** and **NPV**, respectively) and positive and negative likelihood ratios (**PLR** and **NLR**, respectively). To calculate Se, the number of cows presenting an $LS \geq 3$ and an abnormal posture was divided by the total number of cows classified as having an $LS \geq 3$. To calculate Sp, the number of cows presenting an $LS < 3$ and normal posture was divided by the total number of cows classified as having an $LS < 3$. To calculate PPV, the number of cows presenting an $LS \geq 3$ and an abnormal posture was divided by the total number of cows observed with that abnormal posture. To calculate NPV, the number of cows presenting an $LS < 3$ and normal posture was divided by the total number of cows observed with normal posture.

Calculations for PLR $[(Se) / (1 - Sp)]$, and NLR $[(1 - Se) / (Sp)]$ were conducted. Test characteristics for observed postures were compared among methodologies using McNemar's chi-square test. All data analyses were performed with open-source statistical software R (R Development Core Team, 2013). The libraries used from the statistical software R were "arm" (Gelman and Su, 2014), "car" (Fox and Weisberg, 2011), "doBy" (Højsgaard et al., 2013), "epicalc" (Chongsuvivatwong, 2012), "epiR" (Stevenson et al., 2014), "MASS"

(Venables and Ripley, 2002), “pROC” (Robin et al., 2011) and “plyr” (Wickham, 2011). For logistic regression models, the “glm” function from the “stats” package was used; this function estimates the model parameters using the method of maximum likelihood estimation where estimates are found using an iteratively (re-)weighted least squares algorithm (R Core Team, 2013).

3. Results

3.1. Lameness prevalence, intra-observer, and inter-observer agreement

Lameness prevalence based on postural observations during locomotion score for cows evaluated with S methodology (n = 2,009) was 8.4% (LS 3) and 2.0% (LS 4) whereas 67.6% (LS 1) and 22.1% (LS 2) were classified as sound. Lameness prevalence for cows evaluated based on MPP methodology (n = 2,274) was 8.3% (LS 3) and 2.3% (LS 4) whereas 66.9% (LS 1) and 22.5% (LS 2) were classified as sound. None of the cows evaluated for the study had an LS = 5.

Locomotion score agreement between researcher’s observations and WSU training cases was 76.2% (weighted kappa 0.79) and 76.2% (weighted kappa 0.77) for researchers AG and NS, respectively. Intra-observer agreement of abnormal postures detection ranged from 94.9% (kappa 0.64) to 100% (kappa 1.00) and from 96.1 (kappa 0.28) to 100% (kappa 1.00) for researchers AGM and NS, respectively (Table 1).

3.2. Association between abnormal postures at S and locomotion score

The percentage of cows (n = 2,009) showing one, two, or three postural abnormalities while standing at the head locker stanchions was 13.0, 3.6, and 0.2%, respectively; no cow presented four postural abnormalities simultaneously (Figure 1). The most common anomaly

was HockS (9.6%; n = 192), followed by ArchS (7.5%; n = 150), FavS (2.5%; n = 48), and StanceS (1.4%; n = 28).

The univariable logistic regression indicated that ArchS, HockS, and FavS were potential good predictors of lameness based on $LS \geq 3$ ($P < 0.05$), but not StanceS ($P = 0.494$). Cows observed with ArchS had almost 9.0 times greater odds of lameness compared with cows without ArchS (OR = 8.9, 95% CI: 6.2–12.8). Cows with FavS had 5.6 times greater odds of lameness (95% CI: 3.1–10.2) compared to cows without FavS, while animals observed with HockS had 2.4 times greater odds of lameness (95% CI: 1.6–3.5) than cows with no HockS posture. The univariable logistic regression indicated that DIM (OR = 1.0, 95% CI: 1.0–1.0) and AVKM (OR = 1.0, 95% CI: 1.0–1.0) were not good predictors of lameness, whereas LACT (OR = 2.0, 95% CI: 1.8–2.3) was a potential good predictor of lameness. The final multivariable logistic model included the effects of LACT, ArchS, and FavS whereas HockS was forced as confounder of ArchS (Table 2). The fit of the final multivariable logistic regression model was adequate based on the Hosmer-Lemeshow goodness-of-fit test ($P = 0.63$).

3.3. Association between abnormal gait and postures at MP and locomotion score

Cows (n = 2,274) showed one (10.2%), two (2.1%), or three (0.2%) abnormal postures; 87.5% of the cows did not show any postural abnormality (Figure 2). The most prevalent postural abnormality was ArchMPP (10.7%), followed by HockMPP (1.8%), FavMPP (1.8%), and GaitMPP (0.9%).

The univariable logistic regression indicated that GaitMPP (OR = 8.8; 95% CI: 3.6–21.4), ArchMPP (OR = 8.2; 95% CI: 6.0–11.1), FavMPP (OR = 6.7; 95% CI: 6.5–12.7), and HockMPP (OR = 2.8; 95% CI: 1.4–5.8) had greater odds of lameness. The final logistic regression model included ArchMPP, FavMPP, HockMPP, LACT and the interaction of

LACT and ArchMPP (Table 2). HockMPP was forced into model as confounder of ArchMPP. GaitMPP was removed from the final model as it was collinearly dependent of FavMPP and lack of overall significance in the model. The Hosmer-Lemeshow goodness-of-fit test indicated an adequate fit of the final multivariable logistic regression model ($P = 0.17$).

For cows not showing arched back, the OR of being lame increased by 2.06 as lactation number increased. However, the OR of being lame decreased by 0.66 with lactation for cows with arched back. The areas under the ROC curve for model built with postures obtained at S (0.80, 95% CI: 0.77 – 0.84) and MPP (0.81, 95% CI: 0.78–0.84) were not statistically different ($P = 0.74$).

3.4. Test characteristics

Postures included in the final logistic regression models and all their possible combinations were evaluated as diagnostic methods for lameness detection (Table 3). Using LS as the reference method, both S and MPP lameness detection methods showed the greatest Se for ArchS (0.31) and ArchMPP (0.39), with the Se for ArchMPP greater when analyzed using McNemar's chi-square test ($P = 0.034$). Overall, Sp values were high for both MPP (range: 0.93 to 0.99) and S (range: 0.91 to 0.98). The Sp for arch back was statistically significantly greater ($P = 0.023$) for ArchS than ArchMPP, but the difference had minimal biological implications. Overall, PPV was meager, ranging from 0.20 (HockS) to 0.43 (ArchS). Combining the various observed postures, Se reached 0.41 and 0.40 for S and MPP respectively.

3.5. Hoof Lesion Assessment

Cows selected for hoof evaluation ($n = 104$) were detected based on LS ($n = 18$), S [FavS ($n = 22$), two or more abnormal postures ($n = 33$)], MPP [FavMPP ($n = 9$), two or more abnormal postures ($n = 12$)], or through a combination of LS, MPP, and S ($n = 10$). The 104 selected cows had LS 1 ($n = 33$), LS 2 ($n = 22$), LS 3 ($n = 25$), and LS 4 ($n = 24$). A total of 70.8, 65.5, and 56.7% lesions were detected among cows selected based on LS, MPP, and S criteria respectively. The distribution of lesion type by inclusion criteria is shown in Table 4. Overall, 40.4% ($n = 42$) of the enrolled cows showed no lesion or thin soles. There were a total of 49 cows with $LS \geq 3$, and among those, 17 did not show any obvious hoof lesions.

The most prevalent lesions were sole hemorrhage (22.1%), followed by sole ulcers or fractures (16.3%), vertical horn fissure (7.7%), digital dermatitis (6.7%), and white line disease (4.8%). To a lesser extent, we detected interdigital hyperplasia and interdigital phlegmon. Among selected cows, lesions (48.4%) were identified on cows with $LS \leq 2$. However, most of those lesions (70.0%) were classified as mild (score 1 of 3). Lesions (57.1%) detected in $LS \geq 3$ cows, were categorized as moderate or severe (scores 2 and 3).

4. Discussion

The diagnostic characteristics of two lameness identification methodologies, based on observations in stalls and milking parlor, were evaluated on a large California dairy. Although previous studies have been conducted to evaluate the accuracy of detecting digital dermatitis in the milking parlor (Rodriguez-Lanz et al., 1998; Relun et al., 2011; Stokes et al., 2012), to our knowledge the present study is the first one assessing the reliability of the detection of abnormal postures and locomotion disorders observed in the milking parlor as a lameness diagnostic test. The herd lameness prevalence observed in the study was in the

average range previously reported in North America (Cook 2003; Espejo et al., 2006; Ito et al., 2010; Hoffman et al., 2014).

Both lameness detection methodologies, S and MPP, indicated that arched back and favored-limb were postural abnormalities associated with lameness. Our results are consistent with the lameness indicators of Sprecher et al. (1997), where both traits, arched back ($LS \geq 3$) and favoring ($LS \geq 4$), are lameness indicators. Likewise, most lameness scoring systems are based on observation of traits like arched back or spine curvature and favoring (Schlageter-Tello et al., 2014).

Previous research has shown an association between arched back posture and hoof pathologies (O’Callaghan et al., 2003; Flower and Weary, 2006; Chapinal et al., 2009). Using a similar methodology to S for lameness detection, Hoffman et al. (2014) reported a significant association between lameness and arched back, favored-limb, and cow-hocked posture. The association between favored-limb and lameness was expected, as it is a good indicator of painful hoof lesions (Bicalho et al., 2007). However, just a small number of cows requiring a hoof trimmer intervention will exhibit favoring. In our study, favored-limb was observed in 2.39% and 1.76% of cows with S and MPP lameness detection methods respectively.

Wide-stance and cow-hocked postures have also been proposed as signs of lameness (Toussaint-Raven, 1985; Shearer et al., 2012) that could be easily observed on standing cows. Lameness in dairy cattle is mostly associated with disorders of lateral claws of rear feet (Shearer et al., 2012). Those postures could provide pain relief by making the outer claw bear less weight. Cow-hocked posture has also been proposed not only as a response to pain in the lateral claws but also as a heritable condition that predisposes a cow to claw lesions and lameness (Capon et al., 2008). However, in the present study those postures were not significantly associated with lameness. Likewise, Chapinal et al. (2009) indicated that

adduction of hind legs was not a good predictor of sole ulcers. However, Hoffman et al. (2014) found cow-hocked posture associated with lameness. Hind limb deviation from the vertical line could be explained by factors other than lameness such as a large udder or just the normal conformation of the cow. In the present study, evaluations conducted with S methodology were done before milking. Thus, large udders might have forced wide-stance postures on non-lame cows.

Postural and gait abnormalities observed with S and MPP methodologies resulted in acceptable to very good Sp but fairly poor Se. However, a slightly superior Se was observed for ArchMPP than ArchS. This difference could be explained because observations of ArchMPP were performed when cows walked toward the milking parlor or stood in the milking stall, whereas ArchS was only observed on cows standing while restrained in headlocks. Thomsen (2009) evaluated the association between arched back and lameness by observing cows standing freely in the barn before milking. Considering an $LS \geq 3$ as cutoff for lameness definition, the analysis of data reported by Thomsen (2009) resulted in Se (0.38) similar to our results. In contrast, Hoffman et al. (2014) observing restrained cows at stanchions found a 0.63 Se for arched back posture as a lameness test. This difference could be explained by factors associated with the study population and evaluators' skills. Time per cow spent during the evaluation could have had a large impact on test characteristics, but Hoffman et al. (2014) did not report this information. In the present study, locked time at stanchions was kept to a minimum, with 5.5 to 8.3 cows evaluated per minute. One of the objectives of evaluating and testing new techniques for lameness detection is to easily identify cows requiring a hoof trimmer intervention without compromising daily management. Due to the disturbance of daily management and the economic costs associated with each visit to the hoof trimmer, PPV is an essential test characteristic for farmers. Interestingly, Hoffman et al. (2014) reported a PPV for arched back posture of 0.39, similar

to our results. However, with a lameness prevalence of 27% in Hoffman et al. (2014) versus 10.4% in our study, a lower PPV would be expected in the present study. Inversely, Sp described for arched back posture by Hofmann et al (2014) was lower than our findings. Thomsen et al. (2008) reported that a substantial proportion of obviously lame cows did not show signs of an arched back when standing, and proposed that LS systems should be less rigid. This observation is consistent with the outcomes of LS performed in the present study, where ArchS was not observed in 69.2% of cows with $LS \geq 3$ and may affect the Se of the lameness detection based on spine curvature exclusively.

As lactation number increased, the OR of being lame increased for cows that were not observed with arch back at MPP. It is unknown why in our study the more mature lame cows refrained from displaying back arch during milking. At the study dairy, milkers played a key role on lame cows identification. Cows showing arched back at the MPP could have been treated earlier and more aggressively than those that did not display this posture.

Hoffman et al. (2014) reported a meager Se (0.54) and PPV (0.32) for cow-hocked, whereas in our study HockMPP had a very poor Se (0.04) and PPV (0.24). During MPP lameness evaluations, researchers observed competitive behavior at the milking parlor that could have affected rear legs posture and decreased cow-hocked presentation. The herringbone parlor design of the experimental dairy may have favored this behavior. Observation of FavMPP or GaitMPP while cows were conducted from the pens to the milking parlor holding area had a limited Se, but the greatest PPV value for lameness detection. It is noteworthy that lameness detection on dairy farms in San Joaquin Valley (CA) is mainly performed while cows are moved to the milking parlor (Pineda et al., 2015). In our study, only animals walking last received a good visual exam. This can explain the poor Se for lameness detection for FavMPP. However, time-series evaluations of abnormal postures could have improved Se, Sp, and PPV.

S and MPP as lameness-diagnosing methods present some practical limitations. Cows need to be restrained to conduct S methodology. During our evaluations, a non-trivial proportion of cows (11.1%) were not restrained and therefore were not evaluated. We observed that 4.5% of cows not restrained during S evaluations and 2% of cows locked had an LS = 4. This was expected, as lame cows have been shown to spend less time feeding (Yunta et al., 2012; Norring et al., 2014) and more time lying down (Juarez et al., 2003; Chapinal et al., 2009; Ito et al., 2010). To maximize the number of cows locked, it would be advisable to trap cows immediately after feeding. Moreover, as a prey species, cows could display stoic behavior in the presence of an observer (Weary et al., 2009). Thus, if cows hide pain and show a flat back, the Se of lameness detection methodologies could be compromised. Conversely, Leach et al. (2012) suggested that movements caused by flies, nervousness, or other reason not related to hoof pain can be misinterpreted as a signal of weight shifting and thus increase false positive rates.

Detection of abnormal postures during milking procedures could have some practical limitations related to facilities design and time constraints of milkers. To identify ArchMPP postures, milkers have to observe cows while they are walking towards the milking stall. However, on rotary parlors this observation is not possible as there is no walking platform. In addition, the fast cow flow in rotary parlors makes detection of any postural anomaly difficult. Another limiting factor of evaluating cows at the milking parlor is related to cow identification, only feasible when electronic identification systems are available. Overall, based on researchers' experience, implementation of MPP is a very demanding and time-consuming task. Considering that some milking routines are laborious and demand a fast pace, it would be advisable to delegate lameness identification to an operator other than milkers. Taking all these factors into account, future studies should evaluate S as an alternative strategy for lameness identification on dairies.

Even though LS systems are widely used in research, few studies have investigated the relationship between LS and hoof lesions (Thomsen et al., 2012). Any lameness detection method must be validated by the presence of pain and lesions at the hoof level. In the current study, only 104 cows were selected for hoof examination to avoid interfering with management. This restraint forced a convenience sample based on LS > 3, favored-limb posture, or two or more abnormal postures and gait anomalies with S and MPP. Although these criteria were adopted to maximize PPV, not all selected cows presented lesions. Non-lame cows (n = 55; LS 1 and LS 2) were included by criteria other than by LS; 31 of the 55 cows presented lesions. Accordingly, others (O'Callaghan et al., 2003; Tadish et al., 2010; Thomsen et al., 2012) have found hoof lesions in non-lame cows. In a study conducted on 91 Chilean dairy herds, Tadish et al. (2010) found that 64, 53, and 39% of cows with LS 2 showed white line disease, heel erosion, and sole hemorrhage, respectively. The aforementioned study concluded that an LS system is not sensitive enough to predict hoof lesions. Thomsen et al (2012), investigating 1,340 cows from 42 dairy herds, reported lower hoof lesion prevalence in cows with LS 1 (20%) and LS 2 (28%). Inversely, we found 40.0% and 29.2% of the selected cows with LS 3 and LS 4, respectively, lacked hoof lesions. Previous findings indicated the absence of hoof lesions on 21 to 35% of cows with LS 4 (Thomsen et al., 2012; Bicalho et al., 2007).

A different hypothesis could explain the absence of visible hoof lesions in cows with abnormal gait or standing postures. Sole lesions result from corium damage that may have occurred several weeks before (Toussaint-Raven, 1985). This lag from sole injury development to hoof lesion can explain the lack of concordance between LS and presence of lesions. In the current study, hooves were examined at a single session; therefore, lesion progression was not assessed. Long-term studies should validate lameness detection methodologies with hoof lesion evaluations. Gait and postural anomalies could be associated

with pathologies other than hoof lesions. Differentiation between hoof and upper limb lesions can be difficult (Shearer et al., 2012), requiring a diagnostic approach that is not feasible under farm conditions. Although cows observed with upper leg lesions were removed from the study, some enrolled cows might have suffered from undetected limb lesions. Moreover, some diseases that cause abdominal and thoracic pain may explain postures like arched back and could be mistaken for hoof pathologies (Hoffman et al., 2014).

Factors such as cow's conformation, size, and udder fill can affect gait and postures. Based on these distinctive features, an automatic lameness detection system attempted to build individual based models and lameness detection thresholds for each animal (Viazzi et al., 2013). But, cows have showed an inconsistent gait profile over time (Flower and Weary, 2009). Further research is required to better understand validity, reliability, and Se of detection of gait or postural anomalies observed with S and MPP through repeated measures or other technique modifications, considering hoof lesion as reference technique.

5. Conclusions

The present study demonstrates an association between lameness, defined as $LS \geq 3$, and some postural and gait anomalies detected with S and MPP methodologies. However, test characteristics of various postures detected with MPP and S were inadequate for lameness diagnosis. Nevertheless, due to the lack of adoption of LS as the lameness detection method on commercial dairies, it is imperative that future research evaluates modifications of S and MPP lameness detection techniques that could improve their diagnostic value. Our findings suggest lack of concordance between LS, S, MPP methodologies, and visible hoof lesions. Reliability and validity of detection of gait or postural anomalies observed at milking parlor and stanchions, warrant further studies considering hoof lesion as reference technique for lameness detection.

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516 **References**

517 Archer, S. C., Green, M. J., Huxley, J. N., 2010. Association between milk yield and serial
518 locomotion score assessments in UK dairy cows. *J. Dairy Sci.* 93, 4045–4053.

519 Bicalho, R. C., Cheong, S. H., Cramer, G., Guard, C. L., 2007. Association between a visual
520 and an automated locomotion score in lactating Holstein cows. *J. Dairy Sci.* 90, 3294–
521 3300.

522 Burgi, K., Cook, N. B., 2006. Page 179 in *Proc. 14th Int. Symp. on Lameness in Ruminants*,
523 Colonia, Uruguay.

524 Capion, N., Thamsborg, S. M., Enevoldsen, C., 2008. Conformation of hind legs and
525 lameness in Danish Holstein heifers. *J. Dairy Sci.* 91, 2089–2097.

526 Chapinal, N., de Passille, A. M., Weary, D. M., von Keyserlingk, M. A. G., Rushen, J., 2009.
527 Using gait score, walking speed, and lying behavior to detect hoof lesions in dairy cows.
528 *J. Dairy Sci.* 92, 4365–4374.

529 Chongsuvivatwong, V. 2012. *epicalc: Epidemiological calculator*. R package version
530 2.15.1.0. Accessed Sep 21, 2014. <http://CRAN.R-project.org/package=epicalc>

531 Cook, N. B., 2003. Prevalence of lameness among dairy cattle in Wisconsin as a function of
532 housing type and stall surface. *J. Am. Vet. Med. Assoc.* 223, 1324–1328.

533 Cramer, G., 2007. Quantification of foot lesions and an evaluation of early detection methods
534 for lameness in Ontario dairy herds. PhD Thesis. Univ. Guelph, Guelph, Ontario, Canada.

535 Dyer, R. M., Neerchal, N. K., Tasch, U., Wu, Y., Dyer, P., Rajkondawar, P. G., 2007.
 536 Objective determination of claw pain and its relationship to limb locomotion score in
 537 dairy cattle. *J. Dairy Sci.* 90, 4592–4602.

538 Espejo, L. A., Endres, M. I., Salfer, J. A., 2006. Prevalence of lameness in high-producing
 539 Holstein cows housed in freestall barns in Minnesota. *J. Dairy Sci.* 89, 3052–3058.

540 Flower, F. C., Weary, D. M., 2006. Effect of hoof pathologies on subjective assessments of
 541 dairy cow gait. *J. Dairy Sci.* 89, 139–146.

542 Fleiss, J. L., Levin, B., Paik, M. C., 2003. *Statistical Methods for Rates and Proportions*. John
 543 Wiley and Sons, New York, NY.

544 Flower, F. C., Weary, D. M., 2009. Gait assessment in dairy cattle. *Animal*. 3, 87–95.

545 Fox, J., Weisberg, S., 2011. *An R Companion to applied regression*, 2nd ed. Sage
 546 Publications Thousand Oaks, CA.

547 Gelman, A., Su, Y. S., 2014. *arm: Data analysis using regression and multilevel / hierarchical*
 548 *models*. R package version 1.7-03. Accessed Jun 21, 2014. [http://CRAN.R-](http://CRAN.R-project.org/package=arm)
 549 [project.org/package=arm](http://CRAN.R-project.org/package=arm).

550 Hoffman, A. C., Moore, D. A., Vanegas, J., Wenz, J. R., 2014. Association of abnormal hind-
 551 limb postures and back arch with gait abnormality in dairy cattle. *J. Dairy Sci.* 97, 2178–
 552 2185.

553 Højsgaard, S., Halekoh, U., 2013. *doBy - Groupwise summary statistics, LSmeans, general*
 554 *linear contrasts, various utilities*. R package version 4.5-10. Accessed Jun 21, 2014.
 555 <http://CRAN.R-project.org/package=doBy>

556 Huxley, J. N., 2013. Impact of lameness and claw lesions in cows on health and production.
 557 Livestock Sci. 156, 64–70.

558 ICAR Working Group on Functional Traits and International Claw Health Experts, 2015.
 559 ICAR Claw Health Atlas. URL Accessed Sep 21, 2015.
 560 http://www.icar.org/Documents/ICAR_Claw_Health_Atlas.pdf

561 Ito, K., von Keyserlingk, M. A. G., LeBlanc, S. J., Weary, D. M., 2010. Lying behavior as an
 562 indicator of lameness in dairy cows. J. Dairy Sci. 93, 3553–3560.

563 Juarez, S. T., Robinson, P. H., DePeters, E. J., Price, E. O., 2003. Impact of lameness on
 564 behavior and productivity of lactating Holstein cows. Appl. Anim. Behav. Sci. 83, 1–14.

565 Kleinbaum, G. D., Klein, M., 2010 Logistic Regression: a self-learning text, Series Statistics
 566 for biology and health. Third Edition. 2010. Springer-Verlag New York

567 Leach, K. A., Dippel, S., Huber, J., March, S., Winckler, C., Whay, H. R., 2009. Assessing
 568 lameness in cows kept in tie stalls. J. Dairy Sci. 92, 1567–1574.

569 Leach, K. A., Whay, H. R., Maggs, C. M., Barker, Z. E., Paul, E. S., Bell, N. J., Main, D. C.
 570 J., 2012. Working towards a reduction in cattle lameness: 2. Understanding dairy farmers’
 571 motivations. Res. Vet. Sci. 89, 318–323. Leach, K. A., Tisdall, D. A., Bell, N. J., Main, D.
 572 C. J., Green, L. E., 2012. The effects of early treatment for hindlimb lameness in dairy
 573 cows on four commercial UK farms. Vet. J. 193, 626–632.

574 Norring, M., Häggman, J., Simojoki, H., Tamminen, P., Winckler, C., Pastell, M., 2014.
 575 Short communication: Lameness impairs feeding behavior of dairy cows. J. Dairy Sci. 97,
 576 4317–4321.

577 O'Callaghan, K. A., Cripps, P. J., Downham, D. Y., Murray, R. D., 2003. Subjective and
 578 objective assessment of pain and discomfort due to lameness in dairy cattle. *Anim. Welf.*
 579 12, 605–610.

580 Pineda, M., Akin, I., Silva-del-Rio, N., 2015. Survey of lame cow management practices on
 581 California dairies. Page 150 in *Proc. 18th Int. Symposium on Lameness in Ruminants*,
 582 Valdivia, Chile.

583 Potterton, S. L., Bell, N. J., Whay, H. R., Berry, E. A., Atkinson, O. C. D., Dean, R. S., Main,
 584 D. C. J., Huxley, J. N., 2012. A descriptive review of the peer and non-peer reviewed
 585 literature on the treatment and prevention of foot lameness in cattle published between
 586 2000 and 2011. *Vet. J.* 193, 612–616.

587 R Core Team. 2013. R: A language and environment for statistical computing. R Foundation
 588 for Statistical Computing, Vienna, Austria. URL Accessed Jun 21, 2014. [http://www.R-](http://www.R-project.org/)
 589 [project.org/](http://www.R-project.org/).

590 Relun, A., Guatteo, R., Roussel, P., Bareille, N., 2011. A simple method to score digital
 591 dermatitis in dairy cows in the milking parlour. *J. Dairy Sci.* 94, 5424–5434.

592 Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J. C., Müller M., 2011.
 593 pROC: an open-source package for R and S+ to analyze and compare ROC curves. *BMC*
 594 *Bioinformatics*, 12, p. 77. DOI: 10.1186/1471-2105-12-77. Accessed Jun 21, 2014.
 595 <http://www.biomedcentral.com/1471-2105/12/77>

596 Rodriguez-Lainz, A., Melendez-Retamal, P., Hird, D. W., Read, D. H., 1998. Papillomatous
 597 digital dermatitis in Chilean dairies and evaluation of a screening method. *Prev. Vet.*
 598 *Med.* 37, 197–207.

599 Schlageter-Tello, A., Bokkers, E. A., Koerkamp, P. W., Van Hertem, T., Viazzi, S.,
 600 Romanini, C. E., Halachmi, I., Bahr, C., Berckmans, D., Lokhorst, K., 2014. Manual and
 601 automatic locomotion scoring systems in dairy cows: a review. *Prev. Vet .Med.* (1-2), 12–
 602 25.

603 Shearer, J. K., Van Amstel, S. R., Broderse, B. W., 2012. Clinical diagnosis of foot and leg
 604 lameness in cattle. *Vet. Clin. Food Anim.* 28, 535–556.

605 Sprecher, D. J., Hostetler, D. E., Kaneene, J. B., 1997. A lameness scoring system that uses
 606 posture and gait to predict dairy cattle reproductive performance. *Theriogenology* 47,
 607 1179–1187.

608 Stevenson, M., 2014. epiR: An R package for the analysis of epidemiological data. R package
 609 version 0.9-58. Accessed Sep 14, 2014. <http://CRAN.R-project.org/package=epiR>.

610 Stokes, J. E., Leach, K. A., Main, D. C. J., Whay, H. R., 2012. The reliability of detecting
 611 digital dermatitis in the milking parlour. *Vet. J.* 193, 679–684.

612 M. Szklo, and F. Javier Nieto. 2007. *Epidemiology: Beyond the Basics*, Second Edition.
 613 Jones and Bartlett Learning. Burlington MA USA.

614 Tadich, N., Flor, E., Green, L., 2010. Associations between hoof lesions and locomotion
 615 score in 1098 unsound dairy cows. *Vet. J.* 184, 60–65.

616 Thomsen, P. T., Munksgaard, L., Togersen, F. A., 2008. Evaluation of a lameness scoring
 617 system for dairy cows. *J. Dairy Sci.* 91, 119–126.

618 Thomsen, P. T., 2009. Rapid screening method for lameness in dairy cows. *Vet. Rec.* 164,
 619 689–690.

620 Thomsen, P. T., Munksgaard, L., Sørensen, J. T., 2012. Locomotion scores and lying
621 behavior are indicators of hoof lesions in dairy cows. *Vet. J.* 193, 644–647.

622 Toussaint-Raven, E., 1985. *Cattle Footcare and Claw Trimming*. Farming Press, Ipswich,
623 UK.

624 Venables, W. N., Ripley, B. D., 2002. *Modern applied statistics with S*. 4th ed. Springer,
625 New York. ISBN 0-387-95457-0.

626 Viazzi, S., Bahr, C., Schlageter-Tello, A., Van Hertem, T., Romanini, C. E. B., Pluk, A.,
627 Halachmi, I., Lokhorst, C., Berckmans, D., 2013. Analysis of individual classification of
628 lameness using automatic measurement of back posture in dairy cattle. *J. Dairy Sci.* 96,
629 257–266.

630 Washington Univ. CAHNRS Veterinary Medicine Extension. Training Module: How to
631 Locomotion Score Dairy Cows. Accessed May 20, 2013.
632 <http://vetextension.wsu.edu/research-projects/lameness/training/>

633 Weary, D. M., Huzzey, J. M., von Keyserlingk, M. A. G., 2009. Using behavior to predict
634 and identify ill health in animals. *J. Animal Sci.* 87, 770–777.

635 Whay, H. R., Main, D. C. J., Green, L. E., Webster, A. J. F., 2003. Assessment of the welfare
636 of dairy cattle using animal-based measurements: Direct observations and investigation of
637 farm records. *Vet. Rec.* 153, 197–202.

638 Wickham, H., 2011. The split-apply-combine strategy for data analysis. *J. Statistical*
639 *Software*, 40(1), 1–29. Accessed Jun 21, 2014. <http://www.jstatsoft.org/v40/i01/>

640 Yunta, C., Guasch, I., Bach, A., 2012. Short communication: Lying behavior of lactating
641 dairy cows is influenced by lameness especially around feeding time. J. Dairy Sci. 95,
642 6546–6549.

643 Zinpro Corp., 2010. Locomotion score of dairy cattle. Zinpro Corp. Eden Prairie. MN.
644 Accessed May 2013. [http://www.zinpro.com/video-library/dairy-locomotion-](http://www.zinpro.com/video-library/dairy-locomotion-videos#/videos/list)
645 [videos#/videos/list](http://www.zinpro.com/video-library/dairy-locomotion-videos#/videos/list)

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Table 1. Intra-observers agreement of abnormal postures detection at stanchions (S) and when cows were walking to milking parlor or during milking (MPP) for observers 1 and 2.

	Observer 1		Observer 2	
	Kappa (95% CI)	% Agreement	kappa (95% CI)	% Agreement
Arched-back S	0.737 (0.387-1.00)	97.5	1 (1.00-1.00)	100
Wide-stance S	1 (1.00-1.00)	100	0.722 (0.465-0.980)	94.9
Cow-hocked S	0.844 (0.632-1.00)	97.5	0.794 (0.401-1.00)	98.7
Favored-limb S	0.639 (0.312-0.966)	94.9	0.843 (0.631-1.00)	97.5
Cow-hocked MPP	0.902 (0.713-1.00)	98.7	0.282 (-0.712-0.933)	96.1
Favored-limb MPP	0.779 (0.537-1.00)	96.1	0.788 (0.609-0.966)	93.5

Table 2. Final logistic regression models for postures and gait abnormalities observed when cows (n = 2009) were locked at stanchions (S) and when cows (n=2274) were walking to milking parlor or during milking (MPP). Only the odds ratios for the interaction term are shown.

Model	AUC (%) ¹	Final model	Estimated	SE	OR ²	95%CI	P - value
S	80.1	Intercept	-4.19	0.20			<0.001
		Arched back	1.81	0.21	6.1	4.0-9.3	<0.001
		Favored limb	0.88	0.37	2.4	1.2-5.0	0.017
		Cow-hocks ³	0.26	0.24	1.3	0.8-2.1	0.282
		Lact ⁴	0.66	0.06	1.9	1.7-2.2	<0.001
MPP	81.0	Intercept	-4.39	0.21	-	-	<0.001
		Arched back	2.89	0.41	-	-	<0.001
		Favored limb	0.86	0.38	2.4	1.1-5.0	0.023
		Cow-hocks ³	0.59	0.44	1.8	0.8-4.3	0.177
		Lactation	0.72	0.07	-	-	<0.001
		Arched-back*Lact ⁴	-0.42	0.13	0.7	0.5-0.8	<0.001

¹AUC = area under receiver operating characteristic curve;

²OR = odds ratio

³confounder

⁴Lact = Lactation

Table 3. Test characteristics for presence of gait and postural abnormalities included in the final logistic regression model and their combinations as test for lameness (locomotion score ≥ 3) observed when cows were locked at stanchions (S) and when cows were walking to milking parlor or during milking (MPP)¹

Lameness Detection Technique	Posture or combination	Se ¹	Sp	PPV	NPV	PLR	NLR
S	Arched Back	0.31*	0.95*	0.43	0.92	6.44	0.73
	Favored limb	0.09	0.98	0.38	0.90	5.2	0.93
	Cow-Hocked	0.18	0.91	0.20	0.91	2.14	0.89
	Any posture	0.41	0.87	0.27	0.93	3.25	0.67
MPP	Arched Back	0.39*	0.93*	0.39	0.93	5.35	0.66
	Favored limb	0.07	0.99	0.42	0.90	6.26	0.94
	Cow-Hocked	0.04	0.98	0.24	0.90	2.73	0.97
	Any posture	0.40	0.91	0.34	0.93	4.40	0.66

*Significant difference ($P < 0.05$) when comparing diagnostic test characteristics between S and MPP lameness detection techniques.

¹Se = sensitivity; Sp = specificity; PPV = positive predictive value; NPV = negative predictive value; PLR = positive likelihood ratio; NLR = negative likelihood ratio.

Table 4. Description of lesions found on 104 cows observed with locomotion score (LS) > 3, favored-limb (Fav) or two or more abnormal postures (AP>1) when cows were locked at stanchions (S) and when cows were walking to milking parlor or during milking (MPP).

Lesion Type	Lesion, cow (n)	Abnormal Postures, cow (n)				
		S			MPP	
		LS > 3	Fav	AP>1	Fav	AP>1
White Line Disease	5	1	0	1	3	1
Sole Ulcer / Fracture	17	8	4	5	4	3
Sole Hemorrhage	23	5	1	11	1	5
Vertical Horn Fissure	8	1	4	3	0	0
Interdigital hyperplasia	1	0	1	0	0	0
Digital Dermatitis	7	1	2	1	2	2
Interdigital phlegmon	1	1	0	0	1	0
Thin Soles	4	2	1	0	1	1
No lesion	38	5	10	17	3	5
Total	104	24	23	38	15	17

Figure 1. Proportion of lactating dairy cows (n = 2009) observed while locked at stanchions with none (0 S), one (1 S), two (2 S) and three (3 S) postural abnormalities (Panel A), and with wide-stance (StanceS), favored-limb (FavS), cow-hocked (HockS) and arched back (ArchS) postures (Panel B) by locomotion score. No cows were classified with locomotion score 5.

Figure 2. Proportion of lactating dairy cows (n = 2,274) observed during milking or walking to milking parlor with none (0 MPP), one (1 MPP), two (2 MPP) and three (3 MPP) postural abnormalities (Panel A), and with uneven gait (GaitMPP), favored-limb (FavMPP), cow-hocked (HockMPP) and arched back (ArchMPP) posture (Panel B) by locomotion score. No cows were classified with locomotion score 5.