Evaluation of a fully automated 2D imaging system for real-time cattle lameness detection using machine learning

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The STROBE-Vet statement checklist.

	Item	*STROBE-Vet recommendation*	*Page #*
Title and Abstract	1	(a) Indicate that the study was an observational study and, if applicable, use a common study design term	**2**
		(b) Indicate why the study was conducted, the design, the results, the limitations, and the relevance of the findings	**3 – 4**
Background / rationale	2	Explain the scientific background and rationale for the investigation being reported	**6 – 9**
Objectives	3	(a) State specific objectives, including any primary or secondary prespecified hypotheses or their absence	**9**
		(b) Ensure that the level of organization[a] is clear for each objective and hypothesis	**9**
Study design	4	Present key elements of study design early in the paper	**10 – 14**
Setting	5	(a) Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	**10 – 14**
		(b) If applicable, include information at each level of organization	**10 – 14**
Participants [b]	6	(a) Describe the eligibility criteria for the owners/managers and for the animals, at each relevant level of organization	**10 – 13**
		(b) Describe the sources and methods of selection for the owners/managers and for the animals, at each relevant level of organization	**10 – 13**
		(c) Describe the method of follow-up	**NA**
		(d) For matched studies, describe matching criteria and the number of matched individuals per subject (e.g., number of controls per case)	**NA**
Variables	7	(a) Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. If applicable, give diagnostic criteria	**14 – 18**
		(b) Describe the level of organization at which each variable was measured	**14 – 18**
		(c) For hypothesis-driven studies, the putative causal-structure among variables should be described (a diagram is strongly encouraged)	**NA**

Data sources / measurement	8*	(a) For each variable of interest, give sources of data and details of methods of assessment (measurement). If applicable, describe comparability of assessment methods among groups and over time	**14 – 18**
		(b) If a questionnaire was used to collect data, describe its development, validation, and administration	**NA**
		(c) Describe whether or not individuals involved in data collection were blinded, when applicable	**12**
		(d) Describe any efforts to assess the accuracy of the data (including methods used for "data cleaning" in primary research, or methods used for validating secondary data)	**NA**
Bias	9	Describe any efforts to address potential sources of bias due to confounding, selection, or information bias	**11 – 12**
Study size	10	(a) Describe how the study size was arrived at for each relevant level of organization	**11 – 14**
		(b) Describe how non-independence of measurements was incorporated into sample-size considerations, if applicable	**NA**
		(c) If a formal sample-size calculation was used, describe the parameters, assumptions, and methods that were used, including a justification for the effect size selected	**NA**
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why	**14 – 18**
Statistical methods	12	(a) Describe all statistical methods for each objective, at a level of detail sufficient for a knowledgeable reader to replicate the methods. Include a description of the approaches to variable selection, control of confounding, and methods used to control for non-independence of observations	**14 – 18**
		(b) Describe the rationale for examining subgroups and interactions and the methods used	**14 – 18**
		(c) Explain how missing data were addressed	**14 – 18**
		(d) If applicable, describe the analytical approach to loss to follow-up, matching, complex sampling, and multiplicity of analyses	**NA**
		(e) Describe any methods used to assess the robustness of the analyses (e.g., sensitivity analyses or quantitative bias assessment)	**NA**
Participants	13*	(a) Report the numbers of owners/managers and animals at each stage of study and at each relevant level of organization - e.g., numbers eligible, included in the study, completing follow-up, and analyzed	**10 – 13**

		(b) Give reasons for non-participation at each stage and at each relevant level of organization	**NA**
		(c) Consider use of a flow diagram and/or a diagram of the organizational structure	**NA**
Descriptive data on exposures and potential confounders	14*	(a) Give characteristics of study participants (e.g., demographic, clinical, social) and information on exposures and potential confounders by group and level of organization, if applicable	**NA**
		(b) Indicate number of participants with missing data for each variable of interest and at all relevant levels of organization	**NA**
		(c) Summarize follow-up time (e.g., average and total amount), if appropriate to the study design	**NA**
Outcome data	15*	(a) Report outcomes as appropriate for the study design and summarize at all relevant levels of organization	**19 – 25**
		(b) For proportions and rates, report the numerator and denominator	**NA**
		(c) For continuous outcomes, report the number of observations and a measure of variability	**19 – 25**
Main results	16	(a) Give unadjusted estimates and, if applicable, adjusted estimates and their precision (e.g., 95% confidence interval). Make clear which confounders and interactions were adjusted. Report all relevant parameters that were part of the model	**19 – 25**
		(b) Report category boundaries when continuous variables were categorized	**NA**
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	**NA**
Other analyses	17	Report other analyses done,-such as sensitivity/robustness analysis and analysis of subgroups	**NA**
Key results	18	Summarize key results with reference to study objectives	**19 – 25**
Strengths and Limitations	19	Discuss strengths and limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	**35**
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	**25 – 34**
Generalizability	21	Discuss the generalizability (external validity) of the study results	**35**
~~Funding~~ Transparency	22	(a) Funding- Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based (b) Conflicts of interest-Describe any conflicts of interest, or lack thereof, for each author	**(a) 36** **(b) 36** **(c) 36**

		(c) Describe the authors' roles- Provision of an authors' declaration of transparency is recommended (d) Ethical approval- Include information on ethical approval for use of animal and human subjects (e) Quality standards-Describe any quality standards used in the conduct of the research	**(d) 10** **(e) NA**

[a] Level of organization recognizes that observational studies in veterinary research often deal with repeated measures (within an animal or herd) or animals that are maintained in groups (such as pens and herds); thus, the observations are not statistically independent. This non-independence has profound implications for the design, analysis, and results of these studies.
[b] The word "participant" is used in the STROBE statement. However, for the veterinary version, it is understood that "participant" should be addressed for both the animal owner/manager and for the animals themselves.
*Give such information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Abbreviated title: LAMENESS DETECTION SYSTEM WITH AI ALGORITHM

Interpretive Summary: Efficient lameness detection is crucial in maintaining health, welfare and productivity of dairy cattle. This study evaluated a fully automated 2-dimensional imaging system employing machine learning to provide real-time mobility score predictions. The system was tested on eleven commercial farms, showing a performance comparable to that of experienced human assessors in detecting lame cows and cows with foot lesions. When using daily mobility scores generated over 30 days before trimming, the system's accuracy was improved and outperformed the human assessor. This advanced technological application offers potential for early detection of lame cows and effective management of lameness in dairy herds.

Evaluation of a fully automated 2D imaging system for real-time cattle lameness detection using machine learning

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Abstract

Early detection and prompt treatment of lame cows are crucial for proactive lameness management. This study aimed to evaluate a fully automated 2-dimensional imaging system for real-time lameness detection using artificial intelligence. Data were collected from eleven dairy farms in the U.K. Four trained veterinarians performed 42 mobility scoring sessions using a 0-3 four-grade scoring system, with scores 2 and 3 representing lameness. On each session, individual weekly average scores were calculated. This resulted in 40,116 paired human mobility scores (**HMS**) and weekly average mobility scores generated using artificial intelligence (**AIMS**) matched to a cow ID. Categorical agreement for the four-grade scale was estimated by calculating the weighted Cohen's kappa ($\boldsymbol{\kappa_w}$) and Gwet's agreement coefficient ($\mathbf{AC_2}$), and for the two-grade scale (non-lame vs. lame) by calculating the percentage agreement (**PA**), unweighted Cohen's kappa ($\boldsymbol{\kappa}$) and Gwet's coefficient ($\mathbf{AC_1}$). A trained veterinarian recorded the presence and severity of any lesion of 2,515 cows, which also had an AIMS assigned. A subset of 758 cows were also assigned an HMS 1-3 days before trimming. Sensitivity (**Se**), specificity (**Sp**) and accuracy (**Acc**) were calculated to describe the system's and human's ability to detect cows with foot lesions. Additionally, automated mobility scores were retrieved for cows with foot lesion records up to 30 days before trimming. Linear mixed effects models (**LMM**s) were built to assess the association of the lesion status at trimming with the daily scores. The average (**mAVG**), maximum (**mMAX**), minimum (**mMIN**) and the percentage of scores that a cow was identified as lame (**mPLS**) during the 30 days before foot trimming were calculated and their Se, Sp and Acc in detecting foot lesions were determined. Lastly, longitudinal data were obtained from 143 cows tracking daily scores from 5 to 64 DIM. The association of lesion status at the early lactation routine trim (**ELRT**) with the daily scores was assessed by fitting LMMs. Regarding the four-grade scale agreement between HMS and AIMS, κ_w (0.24 - 0.34) represented fair agreement, while AC_2 (0.81 to 0.93) almost perfect

agreement. For the two-grade scale agreement, PA was consistently above 80%, κ (0.23 – 0.38) represented fair agreement and AC_1 (0.76 – 0.83) substantial to almost perfect agreement. The AIMS detected cows bearing severe lesions with Se = 0.53 and Sp = 0.74, while the HMS achieved Se = 0.60 and Sp = 0.78. Using optimal thresholds for mAVG, mMAX, mMIN and mPLS the system achieved higher Se than HMS. Moreover, cows with severe lesions had increased scores from 23 days before trimming compared to cows with mild and moderate lesions. Longitudinal data showed that cows with severe lesions at ELRT had higher mobility scores during the first 60 DIM compared to those with mild or moderate lesions. Overall, the system's performance was comparable to that of experienced human assessors in detecting lame cows and cows with foot lesions. Finally, its capability to detect mobility changes before the development of severe lesions highlights its potential for early intervention, which could enhance lameness management in dairy herds.

Keywords: artificial intelligence; convolutional neural network; foot pathologies; locomotion; mobility

Introduction

Lameness in dairy cattle is described as a clinical symptom, representing underlying pathologies, with foot lesions being the most common cause (Murray et al., 1996). Digital dermatitis (**DD**) is the most important infectious cause of lameness, whilst claw horn disruption lesions, the collective term used for lesions such as sole ulcers (**SU**), sole hemorrhage (**SH**) and white line disease (**WL**), are the main non-infectious lameness causing lesions (Murray et al., 1996; Cramer et al., 2008). Lameness is prevalent worldwide (Thomsen et al., 2023) and associated with significant and wide-ranging adverse effects to cow welfare (Whay et al., 1997; Whay and Shearer, 2017) and production efficiency (Charfeddine and Pérez-Cabal, 2017; Omontese et al., 2020). Furthermore, it has the potential to seriously damage public perception of the industry as it is an easily recognized indicator of poor animal welfare (Jackson et al., 2022).

Chronically lame cows have a much-reduced response rate to treatment compared to animals treated promptly (Thomas et al., 2015, 2016). This is thought to be due to pathological changes to the pedal bone and digital cushion structures, which compromise their functionality, creating an environment conducive to a reduced treatment response and an increased risk of developing future lesions (Newsome et al., 2016; Randall et al., 2018; Wilson et al., 2021). Early detection and prompt and effective treatment is a key component in reducing lameness prevalence on dairy farms (Pedersen and Wilson, 2021) and is hypothesised to reduce the risk of pathological change, thereby improving treatment outcomes (Wilson et al., 2022).

Lameness detection has traditionally relied upon humans performing visual assessment of mobility using mobility/locomotion scoring systems. Depending on the system, either or both posture and gait are assessed to detect discomfort (Sprecher et al., 1997; Whay et al., 2003; Flower and Weary, 2006). The Agricultural and Horticultural Development Board (**AHDB**) 0-3 four-grade mobility scoring system is predominantly used in the U.K. (Whay et

al., 2003). Mobility scoring is inexpensive and unobtrusive, and can facilitate early treatment when employed frequently, resulting in improved cure rates (Alawneh et al., 2012; Leach et al., 2012; Groenevelt et al., 2014). However, the frequency of mobility scoring undertaken on U.K. dairy farms varies considerably, which to the authors' experience is often determined by requirements from milk processors to improve animal welfare, with some farms scoring weekly, whilst others score quarterly. Furthermore, some farms do not routinely mobility score, and instead rely on an *ad-hoc* approach to detect lameness by observing cows when walking into the milking parlour, or through the detection of lesions at foot trimming (Griffiths et al., 2018). Farmer estimated lameness, without the use of mobility scoring systems, have been shown to be a poor lameness detection method (Espejo et al., 2006; Fabian et al., 2014; Beggs et al., 2019).

Human mobility scoring does however have some drawbacks. It is time consuming, particularly for large herds, and labour intensive, both of which are listed by farmers as considerable barriers to implementation (Leach et al., 2012). Human mobility scoring is subjective by nature. The Register of Mobility Scorers in the U.K. aims in ensuring that accredited scorers follow consistent professional standards (RoMS, 2024). The background and training of the observer, as well as location, environment and cow-flow can all create variability contributing to low intra- and inter-observer reliability (Van Nuffel et al., 2015; Nejati et al., 2023; Siachos et al., 2024). The presence of an observer can alter cow behaviour which further complicates the accuracy of mobility scoring, with mild to moderate lameness often hidden in an effort to mask vulnerability (Van Nuffel et al., 2015). Yet alterations in cow behaviour are not uniform and have been shown to be farm specific, reflecting the interaction between individual cow factors such as age and cattle handling (Waiblinger et al., 2003).

Technology is increasingly being adopted in modern dairy farming to address welfare challenges. There has been an increasing number of systems developed to identify lame cows

using various kinetic, kinematic and indirect methods, at different levels of automation and applicability (O'Leary et al., 2020; Nejati et al., 2023; Siachos et al., 2024). However, of the current welfare-based sensors available commercially, only a few have been independently validated (Stygar et al., 2021). One such system has been recently developed and commercialized by CattleEye Ltd (Belfast, United Kingdom). Initial validation across three farms has identified that this system performs comparably to two well-trained observers (Anagnostopoulos et al., 2023). Furthermore, when examining the system's ability to detect lesions during foot trimming in a limited number of cows, low sensitivities and high specificities were described for visual mobility scoring, with automated lameness detection displaying greater sensitivity than visual mobility scoring, but reduced specificity (Anagnostopoulos et al., 2023). As causes of lameness, lameness prevalence, herd demographics and environmental conditions could vary substantially across farms, and so there is a need to further validate this system across more farms and using larger datasets.

The timing of the initial corium insult leading to non-infectious lesions and the temporal relationship between lameness and lesion development remain unclear (Hoblet and Weiss, 2001). Moreover, infectious lesions, cases of DD in particular, show a dynamic transition from active and painful lesions to healed or chronic cases that may serve as reservoir of the causative *Treponema* spp. in the environment (Döpfer et al., 2012; Nielsen et al., 2012). A longitudinal analysis of daily mobility scores, alongside the development of lesions could provide insights into these relationships. By identifying cows at risk of lesion development, the intervention would prevent the development of more severe lesions, thereby improving cure rates (Leach et al., 2012; Groenevelt et al., 2014). Swartz et al. (2024) recently collected foot trimming records from three North American dairy farms using CattleEye. They demonstrated that cows with lesions had increased median weekly scores across four weeks before the trimming date compared to those without any reported lesions. Cows with a SU had the highest median

weekly scores preceding trimming. Cows with a WL had the largest score increase, while cows with a case of DD had the lowest median scores and relative score increase among cows with lesions.

Our objective was to further evaluate the lameness detection performance of the CattleEye system in dairy cows using a large dataset of mobility scores and foot lesion records. To achieve this objective we investigated: a) the agreement between a large number of mobility scores across many farms provided by CattleEye and those provided by multiple assessors using a visual mobility scoring system, b) the accuracy of the mobility scores provided by CattleEye and a trained human assessor in detecting the presence of foot lesions recorded consistently by a trained human assessor across a large number of cows, and c) the temporal association between mobility scores provided by the CattleEye system and the development of foot lesions during the lactation period using longitudinal data.

Materials and Methods

Ethics statement

The study was approved by the University of Liverpool Veterinary Research Ethics Committee (Reference VREC1079).

Farms and animals

We collected data from July 2022 to March 2024. Eleven commercial large-size dairy farms designated as A-K, located in Wales, West and South England, participated in this study. Farms were milking approximately 1,000, 2,300, 800, 2,100, 760, 800, 600, 2,100, 1,500, 630 and 2,800 Holstein cows three times per day.

Automated mobility scoring system

The automated mobility scoring system evaluated here has been developed and commercialized by CattleEye Ltd. (Belfast, U.K.). All participating farms were equipped with a 2-dimensional surveillance camera placed over a passageway at the exit of the milking parlor at a height of 4 m above the ground. Details about the camera setup and the functional characteristics of the system have been provided in a previous publication (Anagnostopoulos et al., 2023). Briefly, the camera captures overhead footage of cows walking through a passageway. Footage during one milking is sent to the company's servers, stored in the cloud, and processed. At first, an object-tracking algorithm identifies the outline of each cow, coat pattern and head shape and assigns the identification number (ID) of the individual animal to the recording. The system can also pull information about the cow ID from the sorting gates or the radio-frequency identification system available in the farm. Specific anatomical key points are marked, and their coordinates are followed across frames. These are then processed by a convolutional neural network architecture which produces a mobility score prediction. The system produces a mobility score on a continuous scale from 0 to 100 (from perfect mobility to severe lameness), with each 25-points increment corresponding to one grade on the 0-3 four-grade U.K. AHDB scoring system, with scores 2 and 3 considered as lame (Whay et al., 2003).

For the purpose of this study, individual daily mobility records were available for each cow; and weekly average scores were also calculated. The system's four-grade converted weekly average mobility score will be hereinafter referred as **AIMS**, and the binary converted score (non-lame: scores 0 and 1; lame: scores 2 and 3) as **AIMS_BIN**.

Human mobility scoring records

Four human assessors, namely **HA1** (NS), **HA2** (BG), **HA3** (AA) and **HA4** (GO) performed a total of 42 whole-milking-herd mobility scoring sessions. All four HAs were qualified veterinarians and experienced mobility scorers with HA1, HA2 and HA3 being RoMS

accredited (Register of Mobility Scorers Limited, Wimborne, U.K.) and HA4 having 20-years of experience in cattle lameness research.

During each session, a single HA mobility scored the entire milking herd using the four-grade AHDB scoring system as cows were exiting the milking parlour during the mid-day milking, as the cows walked on level, good quality concrete. Several sessions performed on Farm D (8 sessions) and one on Farm H included only specific milking groups and not the whole herd. Recording was performed mainly using a voice recorder or by manually writing down the cow ID (freeze brand number located at the rear thigh area on either side of the tail, or ear-tag number when the freeze brand was not clear) and the mobility score on spreadsheets attached in a clipboard. All records were then transcribed into Excel spreadsheets. The four-grade (0/1/2/3) and the binary converted human mobility scores (0,1/2,3) will be hereinafter referred to as **HMS** and **HMS_BIN**, respectively.

The AIMS at the same visit-day were also available and stored. Human assessors had no access to the automated mobility records; CattleEye Ltd did not have access to HMS. At the end of the study, HMS and AIMS were matched using the date and the cow ID.

To assess the inter-observer agreement between trained human scorers, HA1 and HA2 visited Farm D on the same day and scored approximately 780 cows during the morning and the afternoon milking, respectively.

Foot lesions data

We collected data during 61 foot-trimming sessions in five of the participating farms (A, D, H, I and K). Cows in these farms were housed all year round in typical 2-row and 3-row free stall barns with grooved concrete floors and were foot-bathed daily. All sessions were performed by professional foot trimmers, and they included both routine and therapeutic trims,

with HA1 being blind to which cows were presented. The presence of any lesion in all four feet of 2,698 cows were consistently recorded according to the International Committee for Animal Recording claw health atlas (Egger-Danner et al., 2014) and the severity of each lesion was graded. Definition and grading methodology used is described in Supplemental Table S1 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024). More than 90% of the assessments were performed by HA1, and the rest were performed by HA3, a qualified veterinarian who followed the same definition and grading methodology.

Cows were classified into three categories according to their foot lesion status as follows:

Status 1 or "Mild" included cows with no lesions or bearing mild lesions: double sole (**DS**), heel horn erosion (**HHE**), sole haemorrhage (**SH**) of grade 1, white line disease (**WL**) of grade 1, axial wall fissure (**AWF**) of grade 1 and digital dermatitis (**DD**) of grade 1.

Status 2 or "Moderate" included cows bearing at least one lesion of moderate severity: sole ulcer (**SU**) of grade 1, SH of grade 3, WL of grade 2, AWF of grade 2, interdigital hyperplasia (**IH**) of grade 1 and 2, interdigital phlegmon (**IP**) of grade 1, and DD of grade 2.

Status 3 or "Severe" included cows bearing at least one severe lesion: SU of grade > 1, WL of grade 3, AWF of grade 3, toe ulcer (**TU**) of grade > 0, IH of grade 3, IP of grade 2 and DD of grade 3.

We also recorded any cow presented to the trimmer as lame with an obvious upper limb case of lameness. These cases included injuries, large abscesses, swollen joints, or joint luxation. Moreover, cows presented to the trimmer for re-examination having a hoof block already applied were also recorded. Both types of cases were excluded from the analysis regardless of the presence of foot lesions. Finally, information about the parity and the latest calving date of each cow were collected from each farm's herd management software.

Longitudinal study data

One-hundred and forty-three cows on Farm B that calved between July 28th and September 28th, 2023, were prospectively enrolled in a longitudinal study to compare daily automated mobility scores over time between cows that did or did not develop foot lesions during early lactation. The studied population consisted of 62 primiparous and 81 multiparous cows. The hind feet of all cows were examined by HA1 within 4-10 DIM by removing a thin layer of horn and modelling to examine for the presence of any lesion. Front feet at this stage were not examined to minimize handling stress. The same researcher was present during the early lactation routine trimming sessions, which were performed on this farm at a median of 94 DIM (ranging from 64 to 146 DIM) by a professional foot trimmer and recorded the presence and graded the severity of any lesion in all four feet. The same definition of lesions and grading methodology was followed for the "fresh cow" trim (**FRESH**) and the early lactation routine trim (**ELRT**) as previously described. At the end of this study, the individual daily automated mobility scores on a continuous scale from 5 to 64 DIM were made available to us.

Daily automated mobility scoring data up to 30 days prior to trimming

For cows with foot lesion records we retrieved the individual daily automated mobility scores on a scale from 0 to 100 and we created two new datasets. The first dataset (**PriorDATA1**) included all cows, for whom we retrieved daily scores from 30 days to 1 day before trimming date. Only cows having at least 10 daily scores recorded were included, and for cows with multiple trimming sessions, we chose the earliest one if the interval between sessions was less than 30 days. A total of 1,986 cows met these criteria.

The second dataset (**PriorDATA2**) consisted only of cows that were trimmed between 60 and 120 DIM and we retrieved daily scores from calving day to 60 DIM. Similarly to the

first dataset, only cows having at least 10 scores were included, and for cows with multiple trimming sessions we chose only the earliest one. A total of 615 cows met these criteria.

Statistical analysis

Data were handled and analysed with IBM SPSS v.28 (IBM Corp.; Armonk, NY) and R Studio (v4.3.1; R Core Team, 2023).

Inter-observer agreement

The categorical inter-observer agreement between AIMS and the HMS of each human scorer was assessed by calculating the quadratically weighted Cohen's kappa coefficient ($\boldsymbol{\kappa_w}$) and the quadratically weighted Gwet's coefficient ($\mathbf{AC_2}$). Similarly, the agreement between AIMS_BIN and HMS_BIN of each human scorer was assessed by calculating the percentage agreement (**PA**), the unweighted Cohen's kappa coefficient ($\boldsymbol{\kappa}$) and the unweighted Gwet's coefficient ($\mathbf{AC_1}$). The same metrics were used to assess the inter-observer agreement between HA1 and HA2. The Gwet's coefficients were computed using R Studio (v4.3.1; R Core Team, 2023) and the irrCAC package (Gwet, 2001). We chose to include in our analysis both Cohen's kappa, for consistency and comparability with previous studies, and Gwet's agreement coefficients, which are considered more robust measures of chance-corrected agreement, particularly in situations with low or high prevalence of the tested trait or marginal imbalance (Gwet, 2008).

To interpret PA, we used the conventionally accepted benchmark of accepted reliability of 80% (McHugh, 2012). To interpret κ and κ_w, and AC_1 and AC_2 estimates, we used the recommendations by Landis and Koch (1977), as follows: slight agreement (0.00-0.20), fair agreement (0.21-0.40), moderate agreement (0.41-0.60), substantial agreement (0.61-0.80), and almost perfect agreement (0.81-1.00). Values above 0.60 have been considered as

representing an acceptable level of inter-observer categorical agreement for various health and welfare indices (Gibbons et al., 2012; Schlageter-Tello et al., 2014).

Accuracy in predicting the presence of foot lesions

Using the dataset with foot lesion records, we created confusion matrixes for the overall study population and within each parity class, to calculate sensitivity (**Se**), specificity (**Sp**) and classification accuracy (**Acc**) for AIMS_BIN and HMS_BIN in accurately predicting the presence of "severe" (Status 3) and of "moderate and severe" (merged Status 2 and 3) foot lesions, using the lesion identification and grading methodology previously described as the ground truth.

The formulas to calculate Se, Sp and Acc were:

$$Se = \frac{True\ Positives}{True\ Positives + False\ Negatives}$$

$$Sp = \frac{True\ Negatives}{True\ Negatives + False\ Positives}$$

$$Acc = Se * P + Sp * (1 - P),$$

Where P = prevalence.

The 95% binomial proportion confidence intervals for Se, Sp and Acc were calculated with the "exact" Clopper-Pearson method (Clopper and Pearson, 1934).

Additionally, we calculated Se, Sp and Acc for AIMS_BIN and HMS_BIN in accurately predicting the presence of SH of grade 3, SU of grade ≥ 1, WL of grade 3, TU of grade ≥ 1, or DD of grade 3, separately, for the overall study population. Cases of AWF of grade 3 were merged with those of WL of grade 3, as considered of similar origin and create the same level of pain and discomfort to the cow. Only cases without severe co-existing lesions were considered as negative controls.

311 *Data from longitudinal study*

312 Cows were classified according to findings at FRESH, as having at least one case of
313 moderate and severe lesion (Status 1 vs. merged Status 2 and 3) or not, and into three classes
314 (Status 1, 2 or 3) according to ELRT findings. Furthermore, we created a second dataset by
315 excluding cows that were diagnosed at ELRT with moderate or severe lesions other than SH
316 grade ≥ 2 or SU of any grade. This resulted in 130 cases with SH/SU status.

317 To assess the association of ELRT lesion status with the daily automated mobility scores
318 from 5 to 64 DIM, we used linear mixed models with repeated measurements. Two separate
319 models were fitted, with A) ELRT lesion status (3 levels: Status 1, 2 and 3), and B) binary
320 SH/SU status (1: cases at ELRT with SH grade ≥ 2 or SU of any grade, 0: rest) as the main
321 fixed effects of interest. Parity (2 levels: primiparous vs. multiparous), DIM, FRESH status
322 (binary) as main effects and all 2-way interactions were the other explanatory and adjusted
323 variables fitted as fixed effects in both models. Days-in-milk were used to specify the repeated
324 measurements statement, accounting for the random effect of the cow.

325

326 *Retrospective assessment of automated mobility scores up to 30 days prior to trimming*
327 Using PriorDATA1, we used linear mixed effects models (**LLM**s) with repeated measurements
328 to assess retrospectively the association of the foot lesion status at trimming with the automated
329 mobility scores from 30 days to 1 day before the trimming session. Three separate models were
330 fitted with the inclusion of: A) Overall Lesion Status (**OLS**) at 3 levels ("mild"; "moderate";
331 "severe"), B) binary OLS (**OLS_BIN_SEV**, defined as: "mild and moderate" vs. "severe"),
332 and C) binary OLS (**OLS_BIN_MODSEV**, "mild" vs. "moderate and severe") as the main
333 fixed effect of interest. Farm (5 levels), parity (4 levels: 1st, 2nd, 3rd, 4th or greater) and days
334 before trimming (**DBT**), as main effects and all 2-way interactions were the other explanatory

and adjusted variables fitted as fixed effects in all models. Days before trimming were used to specify the repeated measurements statement, accounting for the random effect of the cow.

Similarly, using PriorDATA2, we fitted 3 separate models, following the same parametrisation for OLS, to assess the retrospective association of the foot lesion status at 60 – 120 DIM, with the daily automated mobility scores from the day of calving to 60 DIM. Besides OLS, farm (5 levels), parity (4 levels: 1^{st}, 2^{nd}, 3^{rd}, 4^{th} or greater) and DIM, as main effects and all 2-way interactions were the other explanatory and adjusted variables fitted as fixed effects in all models.

Data analysis using LMMs described in the previous two sub-sections was undertaken using R Studio (v4.3.1; R Core Team, 2023), with the Tidyverse (Wickham et al., 2019), nlme (Pinheiro et al., 2023), and emmeans (Lenth, 2023) packages. Model building strategy and model fit procedures were the same across all LMMs. Univariable analyses were performed as an initial exploratory analysis on the independent variables to be included in the LMMs. For each model, the appropriate covariance structure producing the best fit was selected based on the lowest Akaike's information criterion value. Where the main variables of interest produced a statistically significant association, final models were built by backwards eliminating explanatory variables with a non-significant association at $P > 0.10$. Normality and homoscedasticity of data were assessed by visual inspection of the fitted values vs. residuals plot and the Normal Q-Q plot, respectively. On each model, pairwise comparisons between the estimated marginal means (**EMMs**) of the different classes of the lesion status variables were performed using Bonferroni's confidence interval adjustment. The EMMs were then plotted against DIM or DBT to visualise the evolution of the automated mobility scores per lesion status class across time.

Optimal thresholds and accuracy for parameters derived from monthly automated mobility scores

Using the PriorDATA1, we calculated for each cow the monthly average (**mAVG**), maximum (**mMAX**), minimum (**mMIN**) score and the percentage of daily scores that a cow was recorded as lame (**mPLS**). Then, receiver operating characteristic (**ROC**) curves were created for each parameter to identify optimal thresholds in accurately predicting the presence of "severe" (status 3) and of "moderate and severe" (status 2 and 3) foot lesions, and Se, Sp and Acc were calculated for each threshold, for the overall study population and within each parity class.

Using the same parameters as test variables on ROC curves, we identified optimal thresholds and calculated the Se, Sp and Acc in accurately predicting the presence of SH of grade 3, SU of grade ≥ 1, WL of grade 3, TU of grade ≥ 1, or DD of grade 3, separately, for the overall study population.

Results

In total, 47,538 HMS were recorded, out of which 44,981 were matched to a cow ID. After merging the HMS and AIMS using the date and the cow IDs, 40,116 paired scores were available for statistical analysis. The number of scored cows and the lameness prevalence recorded by the human assessor and by the system per session are detailed in Supplemental Table S2 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024). Herd level lameness prevalence ranged from 7% to 30% based on HMS and from 2% to 30% based on AIMS.

Inter-observer agreement between human scorers and the system

The inter-observer categorical agreement between the weekly average mobility scores generated by artificial intelligence and the human mobility scores of each HA is summarized

in Table 1 and shown in detail in Supplemental Table S3 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024). Regarding the agreement on the four-grade scale between AIMS and HMS, the Cohen's κ_w ranged from 0.24 to 0.34 representing only fair agreement, while Gwet's AC_2 ranged from 0.81 to 0.93 representing almost perfect agreement. Regarding the agreement on the binary converted two-grade scale between AIMS_BIN and HMS_BIN, the PA ranged from 81.5% to 86.3% being consistently above the benchmark of accepted reliability. Moreover, Cohen's κ ranged from 0.23 to 0.38 representing only fair agreement, and Gwet's AC_1 ranged from 0.76 to 0.83 representing substantial and almost perfect agreement.

Inter-observer agreement between human scorers

Results on the inter-observer agreement between HA1 and HA2 is shown in Table 2. The 4-grade scale agreement produced a Cohen's κ_w and a Gwet's AC_2 of 0.27 (95% CI: 0.21-0.33) and 0.75 (0.95% CI: 0.72-0.78) representing fair and substantial agreement, respectively. The PA for the binary converted scale was 76.7%, while Cohen's κ and Gwet's AC_1 were 0.27 (95% CI: 0.19-0.35) and 0.67 (95% CI: 0.61-0.72) representing fair and substantial agreement, respectively.

Foot lesions data

From the initial dataset of 2,698 cows with foot lesion records, 33 cows had a case of upper limb lameness. One hundred and twenty cows were presented to the trimmer for re-examination and had already a hoof block applied; these cows were excluded from the analysis. Finally, 2,515 cows were assigned an AIMS, while 758 were scored by the same HA one to three days before trimming and were also assigned an HMS. The prevalence and the severity of lesions recorded on a cow-level are shown in Table 3. On a descending order, SH grade 3,

410 DD grade ≥ 2, WL grade 3, and SU grade ≥ 1 were the most prevalent lesions recorded in our
411 population.

412 The overall and per parity measures of accuracy for AIMS_BIN and HMS_BIN in
413 correctly detecting cows bearing foot lesions using the foot lesions data recorded by HA1 as
414 ground truth, are presented in Table 4. The AIMS_BIN achieved an overall combination of Se,
415 Sp and Acc of 0.37 (95% CI: 0.34-0.39), 0.76 (95% CI: 0.73-0.78) and 0.58 (95% CI: 0.56-
416 0.60), respectively, in detecting the presence of "moderate and severe" lesions. The HMS_BIN
417 achieved an overall combination of Se, Sp and Acc of 0.38 (95% CI: 0.33-0.44), 0.84 (95% CI:
418 0.80-0.87) and 0.62 (95% CI: 0.58-0.65), respectively, in detecting the presence of "moderate
419 and severe" lesions. Measures of accuracy varied across parities. Both the automated and the
420 human scores achieved the lowest Se in parity 1 cows (0.12 and 0.21, respectively) and the
421 highest Se in parity 4+ cows (0.46 and 0.58, respectively).

422 Regarding the accuracy in detecting cows bearing at least one case of "severe" lesions,
423 AIMS_BIN and HMS_BIN produced an overall combination of Se, Sp and Acc of 0.53 (95%
424 CI: 0.47-0.58), 0.74 (95% CI: 0.72-0.76) and 0.71 (95% CI: 0.69-0.73), and 0.60 (95% CI:
425 0.50-0.70), 0.78 (95% CI: 0.75-0.81) and 0.76 (95% CI: 0.73-0.79), respectively. Both the
426 automated and the human scores achieved the lowest Se in parity 1 cows (0.26 and 0.33,
427 respectively), while the highest Se for the automated scores we achieved in parity 3 (0.60) and
428 for the human scores were achieved in 4+ cows (0.75).

429 The measures of accuracy for the automated and the human mobility scores in detecting
430 the presence of each lesion separately are detailed in Table 5. The automated system was able
431 to detect the presence of SH grade 3, SU, WL grade 3, TU and DD grade 3 with Se/Sp
432 combinations of 0.40/0.75, 0.52/0.75, 0.55/0.75, 0.64/0.75 and 0.50/0.75, respectively, while
433 the human mobility scores could detect the presence of these lesions with Se/Sp combinations
434 of 0.49/0.81, 0.63/0.81, 0.67/0.81, 1.00/0.81 and 0.38/0.81, respectively.

435

436 *Longitudinal data*

437 Days-in-milk, ELRT × DIM interaction and parity were identified as significant
438 predictors of the daily automated mobility scores variation. The lesion status at FRESH did not
439 produce any statistically significant associations. The plotted EMMs (± 95% CI) for the ELRT
440 × DIM interaction for each lesion status level are displayed in Fig. 1. Cows with severe lesions
441 at the early lactation trim had significantly greater ($P \leq 0.035$) automated mobility scores than
442 both cows with moderate and with mild or no lesions from 36 DIM to 50 DIM, and greater
443 scores ($P \leq 0.046$) than cows with mild or no lesions from 54 DIM to 64 DIM. Primiparous
444 cows had overall lower daily automated mobility scores compared to multiparous by 4.7 points
445 ($P = 0.001$). The EMMs for cows with mild or no lesions were consistently below 40 (ranged
446 from 32 to 39) without any abrupt changes.

447 When we excluded from the analysis cows that had lesions other than SH grade ≥ 2 or
448 SU of any grade at ELRT, we found that DIM and SH/SU status × parity interaction were the
449 only significant predictors of the daily automated mobility scores variation. The overall effect
450 of SH/SU status was not statistically significant ($P = 0.096$). However, the EMMs for
451 automated mobility scores of cows having at least one case of SH grade ≥ 2 or SU of any grade
452 at ELRT were greater ($P \leq 0.045$) compared to cows without these lesions at specific timepoints
453 (DIM 6, and DIM 61-64). Plotted EMMs for the binary SH/SU status by DIM are provided in
454 Supplemental Figure S1 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024).

455

456 *Assessment of daily automated mobility scores up to 30 days prior to trimming*

457 From the LMM using PriorDATA1, parity, farm, and OLS × DBT interaction were the
458 significant predictors of the automated mobility scores variation from 30 days to 1 day before
459 trimming. The EMMs for automated mobility scores of cows with severe lesions were

460 significantly greater ($P \leq 0.027$) than those of cows with moderate and mild lesions from as
461 early as 23 days prior to trimming and were consistently above 40 points from this timepoint
462 onwards (Fig. 2). Cows at $+4^{th}$, 3^{rd} and 2^{nd} parity had overall greater EMMs compared to
463 primiparous cows by 7.1, 5.2 and 3.0 points, respectively ($P < 0.001$).

464 Regarding the LMM with binary lesion status ("mild and moderate" vs. "severe") as the
465 main variable of interest, parity, OLS_BIN_SEV × DBT interaction, farm and DBT were
466 significant predictors of the automated mobility scores variation from 30 days to 1 day before
467 trimming. The EMMs for automated mobility scores of cows with severe lesions were
468 consistently greater ($P < 0.001$) than those of cows with "moderate and mild" lesions during
469 the entire 30 days prior to trimming, and are shown in Supplemental Figure S2
470 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024).

471 Regarding the LMM with binary lesion status ("mild" vs. "moderate & severe"), parity,
472 lesion status (specifically OLS_BIN_MODSEV), farm and DBT were significant predictors of
473 the automated mobility scores variation from 30 days to 1 day before trimming, when merging
474 moderate and severe lesions. The EMMs for automated mobility scores of cows with "moderate
475 and severe" lesions were greater ($P \leq 0.047$) than those of cows with mild lesions during most
476 of the time prior to trimming, and are shown in Supplemental Figure S3
477 (https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024).

478

479 From the LMMs using PrioDATA2 for cows that were trimmed between 60 and 120
480 DIM, parity, OLS × parity interaction, farm, OLS, and OLS × DIM interaction were significant
481 predictors of the automated mobility scores variation during the first 60 DIM. The EMMs for
482 automated mobility scores of cows with severe lesions were greater ($P \leq 0.047$) than those in
483 cows with moderate and mild lesions on several timepoints from 24 to 32 DIM, at 47 DIM, and

from 55 to 60 DIM (Fig. 3). The EMMs of multiparous cows were overall greater compared to primiparous cows by 13.2 points ($P < 0.001$).

Regarding the LMM with the binary lesion status, where mild and moderate lesions were merged into one group and assessed against the severe lesion group (specifically OLS_BIN_SEV), as the main independent variable of interest, OLS_BIN_SEV × DIM interaction, parity, parity × DIM interaction, DIM, farm, farm × parity interaction and OLS_BIN_SEV × parity interaction were significant predictors of the automated mobility scores variation during the first 60 DIM. The EMMs for automated mobility scores of cows with severe lesions were numerically greater compared to those of cows with mild or moderate lesions during the first 60 DIM, with these being greater ($P \leq 0.042$) from 55 to 60 DIM (Supplemental Figure S4; https://data.mendeley.com/drafts/533d5ttydp; Siachos, 2024).

Regarding the LMM with the binary lesion status, where the mild lesion group was assessed against the merged group of moderate and severe lesions (specifically OLS_BIN_MODSEV), as the main independent variable of interest, neither OLS_BIN_MODSEV nor OLS_BIN_MODSEV × DIM interaction yielded any statistical significance.

Optimal thresholds and accuracy for parameters derived from mobility patterns 30 days prior to trimming

Using the PriorDATA1, the optimal thresholds for mAVG, mMAX, mMIN and mPLS in detecting cows with severe and with moderate and severe lesions, with the calculated Se, Sp and Acc, overall and per parity, are presented in detail in Table 6.

Considering the accurate detection of cows with moderate and severe lesions, the overall threshold of 21.2% for mPLS produced the highest Se (0.48, 95% CI: 0.45-0.52), while the threshold of 58.5 for mMAX produced the best discriminative performance with the highest

AUC (0.60, 95% CI: 0.57-0.62) and Acc (0.62, 95% CI: 0.59-0.64). Sensitivities up to 0.67 (for mMAX) were achieved in cows at 3rd parity. None of the parameters (mAVG, mMAX, mMIN and mPLS) yielded a statistically significant AUC to define a classification threshold in cows at 1st parity. The highest AUC with the highest upper CI bound (0.55, 95% CI: 0.49-0.61, $P = 0.095$) was produced for mAVG.

Considering the accurate detection of cows with severe lesions, the overall threshold of 11.9% for mPLS produced the highest Se (0.76, 95% CI: 0.70-0.82), while the threshold of 57.5 for mMAX produced the highest AUC (0.73, 95% CI: 0.0.69-0.76) and the threshold of 45.9 for mAVG produced the highest Acc (0.71, 95% CI: 0.69-0.73). Across parities, the highest Se (0.80, 95% CI: 0.70-0.87) was achieved for mPLS in cows at 3rd parity. The threshold of 46.5 for mMAX produced a notable Se (0.76, 95% CI: 0.43-0.85) in cows at 1st parity, but with relatively poor discriminative performance (AUC = 0.66, 95% CI: 0.54-0.77).

The measures of accuracy for each parameter derived from the automated mobility scores 30 days to 1 day before trimming in detecting the presence of each lesion separately are detailed in Table 7. All parameters produced thresholds with similar AUC in detecting the presence of SH grade 3, but the threshold of 30.5 for mMIN achieved the highest Se (0.62, 95% CI: 0.55-0.68) and the threshold of 64.5 for mMAX achieved the highest Sp (0.89, 95% CI: 0.87-0.90). Similar results were observed for detecting any SU, with the threshold of 29.5 for mMIN achieving the highest Se (0.77, 95% CI: 0.65-0.86) and the threshold of 65.5 for mMAX achieving the highest Sp (0.90, 95% CI: 0.89-0.92). Regarding detection of WL grade 3, the threshold of 57.5 for mMAX produced the best AUC (0.79, 95% CI: 0.74-0.83) with moderate Se (0.74, 95% CI: 0.65-0.81) and Sp (0.71, 95%: 0.68-0.73), while mPLS at 11.9% produced a notably high Se (0.81, 95% CI: 0.74-0.88), but was followed by a low Sp (0.53, 95% CI: 0.51-0.56). None of the examined parameters (mAVG, mMAX, mMIN and mPLS) yielded a statistically significant AUC to define a classification threshold in detecting the few TU cases

recorded. The highest AUC with the highest upper CI bound (0.61, 95% CI: 0.34-0.88, *P* = 0.371) was produced for mAVG. Finally, the thresholds of 54.5 for mMAX and 20.3% for mPLS produced the best Se (0.66 and 0.65, respectively) in detecting DD grade 3, while the threshold of 46 for mAVG produced the highest Sp (0.74, 95% CI: 0.72-0.76) and Acc (0.73, 95% CI: 0.71-0.75).

Discussion

This study evaluated the performance of a fully automated 2D imaging system using machine learning for real-time lameness detection across a large dataset of mobility scores and foot lesions records, collected from eleven commercial U.K. dairy farms. We demonstrated that the system achieved substantial to almost perfect agreement with trained human observers for detecting lameness (when evaluated using Gwet's agreement coefficients) and identified cows with foot lesions with comparable accuracy. Notably, the system showed improved sensitivity in detecting severe lesions compared to human mobility scores, when using optimal threshold of parameters describing the mobility pattern during the last 30 days prior to trimming. Additionally, the system's ability to track mobility changes over time highlighted its potential for earlier detection of cows at risk of developing foot lesions, supporting its use in proactive lameness management.

The inter-observer agreement between the automated system and the human scorers presented variability depending on the metrics used. Regarding the agreement on the four-level absolute scores between AIMS and HMS, obtained Cohen's κ_w indicated only fair agreement, while the quadratically weighted Gwet's AC_2 were within the almost perfect agreement range. Accordingly, HA1 and HA2 attained a Cohen's κ_w that fell within the range of estimates obtained between the system and the human scorers. Gwet's AC_2 was in the substantial

559 agreement range, but it was lower than the overall estimates obtained between the system and
560 any human scorer.

561 When we evaluated the two-level scale agreement between AIMS_BIN and HMS_BIN,
562 we found that PA consistently exceeded the benchmark of accepted reliability, Gwet's AC_1
563 indicated substantial and almost perfect agreement, while Cohen's κ fell within the fair
564 agreement range. The PA between HA1 and HA2 was lower than that for overall measurements
565 between the system and any assessor. Cohen's κ fell within the range of estimates obtained
566 between the system and the human scorers, and Gwet's AC_1 indicated substantial agreement,
567 but was again lower than the overall estimates obtained between the system and any human
568 scorer.

569 This discrepancy between the different metrics could be attributed to a statistical
570 phenomenon called the "kappa paradox", which is defined by low kappa values in the presence
571 of high percent agreement and is affected by marginal distributions and the low or high
572 prevalence of the trait being studied (Byrt et al., 1993; Vanhoudt et al., 2019). Use of kappa
573 has been questioned in several medical studies due to paradoxically poor reliability in
574 disharmony with the percentage level of agreement (Wongpakaran et al., 2013; Cibulka and
575 Strube, 2021). Gwet's coefficient is considered an improved alternative to kappa and a more
576 stable estimate of chance-corrected agreement under low prevalence of the examined trait
577 scenarios (Gwet, 2008).

578 A few studies have evaluated the inter-observer agreement among different assessors
579 when scoring cows on-farm. Thomsen et al. (2008) found weighted kappa values between 0.24
580 and 0.68 among 5 different observers using a 5-level scale. Linardopoulou et al., (2022) found
581 a wide range of kappa values (0.00-0.57) among human scorers on a 2-level agreement.
582 Anagnostopoulos et al. (2023) reported a Cohen's $\kappa_w = 0.41$ and Gwet's $AC_2 = 0.85$, for the 4-
583 grade scoring, and PA = 88.2%, Cohen's κ = 0.42 and Gwets's AC_1 = 0.81 for the binary

584 converted classification into lame or non-lame. Improved inter-observer agreement metrics
585 have been reported in studies evaluating mobility from video recordings. Gardenier et al.
586 (2021) reported PA = 56% and κ_w = 0.59 for the 4-level scale, and PA = 79% and κ = 0.57 for
587 the 2-level scale, respectively, using the Dairy Australia Healthy Hooves 4-point locomotion
588 system on videos from 50 cows. Similarly, Schlageter-Tello et al. (2014) reported PA = 57%
589 and κ_w = 0.65 on the 5-level scale, and PA = 85.2% and κ = 0.70 for the 2-level scale, among
590 10 observers using a 5-point locomotion scoring system on 58 videos of cows equally
591 representing all locomotion scores.

592 Our results suggest that the system's weekly average mobility scores align well with
593 human observations, comparable to the level of agreement reported in the literature between
594 trained human assessors scoring on-site and to that between HA1 and HA2. Unlike humans,
595 the system is capable of consistently scoring large numbers of cows daily without fatigue or
596 disruptions in cow flow, minimizing the variability linked to different backgrounds and levels
597 of experience (Garcia et al., 2015).

598

599 The automated system showed reasonable accuracy in predicting the presence of
600 moderate and severe lesions. Using AIMS_BIN, the system achieved the same overall Se as
601 with HMS_BIN (0.37 vs. 0.38), and even surpassed the human scorer in parity 3 cows, although
602 the human was always more specific. Both the system and the human were less sensitive and
603 more specific in heifers, this would lead to more heifers bearing foot lesions to remain
604 undetected relative to older cows. The AIMS was more sensitive in older cows, meaning that
605 more cows with foot lesions were correctly identified. This variability in the obtained Se across
606 parities, is in accordance with previous findings with human mobility scoring reported by
607 Logan et al. (2024) and implies that signs of lameness in heifers are more subtle than in older
608 cows. The higher prevalence of lesions in older cows could likely be another explanation.

Although Se and Sp are theoretically unaffected by the prevalence of the tested trait, evidence suggests that higher prevalence is associated with improved Se and lower Sp estimations (Murad et al., 2023). Considering this, a parity-specific calibration of the system's algorithm or lowering the predetermined cut-off of 50 to define lameness in heifers may be worth considering. Logan et al. (2024) reported similar Se and Sp for mobility scoring using the AHDB scoring system in detecting cows with moderate lesions (case definition 2 in their study); a classification that excluded minor lesions and is comparable to the merged Status 2 and 3 used in our study. However, the way the mobility scoring was performed, and the single scorer's background, training and level of experience are not clearly described in their study. Further validation of mobility scoring as a means to identify mild lesions is required, with clear descriptors of mobility scoring training and implementation.

Both AIMS_BIN and HMS_BIN demonstrated improved Se and Acc in detecting cows with at least one severe lesion. The system's performance was comparable to that of the human, but the human was generally more sensitive (0.60 vs. 0.53). The HMS_BIN achieved notably high Se in parity 4+ cows and AIMS_BIN in parity 3 cows, but at the expense of Sp. Although cows with obvious upper limb lameness were excluded, a thorough clinical examination was not conducted systematically, which may have allowed musculoskeletal issues unrelated to foot lesions in older cows to go undetected, reducing specificity. It is interesting to note that in our study both the system and the human achieved higher Se compared to the findings of Logan et al. (2024) in detecting cows with severe lesions (case definition 3 in their study). However, human mobility scoring in Logan et al. (2024) was highly specific (overall Sp = 0.94). In their study, Logan et al. (2024) reported much lower Se in heifers for detecting the presence of moderate and severe lesions (0.07 and 0.09, respectively) compared to our study, although the confidence intervals were wide. Variability across farms between the two studies, especially in the way mobility scoring was performed and case definition (i.e. the threshold for a case

634 definition of lameness may have been lower in the current study), are likely causes for the
635 observed differences in detecting foot lesions.

636 Using individual automated mobility scores tracking back 30 days prior to trimming, we
637 determined optimal thresholds for mAVG, mMAX, mMIN and mPLS. The use of any of these
638 parameters resulted in improved Se in detecting moderate and severe lesions over the
639 AIMS_BIN and the HMS_BIN, without significant decreases in Sp and Acc, although the
640 human scorer remained more specific throughout. However, this was not the case for 1st parity
641 cows where none produced a significant improvement in classification. Generally, the best
642 approach to maximize Se (i.e. produce more true positives and fewer false negatives), would
643 be to target cows that were scored as lame by the system for approximately more than a fifth
644 of the times they were scored, whereas to maximize Sp (i.e. produce more true negatives and
645 fewer false positives), it is best to target cows whose maximum score in the past month
646 exceeded 58.5.

647 The use of any of the parameters derived from mobility patterns 30 days prior to trimming
648 (mAVG, mMAX, mMIN and mPLS) led to improved Se in detecting the presence of severe
649 lesions over the AIMS_BIN, but at the expense of Sp. The thresholds produced for mMAX and
650 mPLS achieved an overall Se higher than that of HMS_BIN, but the human scorer was more
651 specific. Remarkably high sensitivities were obtained for mAVG and mMAX in detecting
652 severe lesions in heifers (0.71 and 0.76, respectively), specificity though was poor. To
653 maximize Se, targeting cows identified by the automated system as lame over 12% of the time
654 in the past month is advisable. Whereas to maximize Sp it is advisable to target cows with an
655 average score above 46 in the past month.

656

657 To the best of our knowledge, there are no studies evaluating the accuracy of any mobility
658 or locomotion scoring system detecting different foot lesions separately. The HMS_BIN was

able to correctly detect all cows with TU, although cases were few, and cows with severe WL or with SU of any grade with sufficient Se (over 0.60). Detection of severe SH had a moderate Se, while Se for detection of DD grade 3 (the active M.2 lesions) was poor. The AIMS_BIN could detect TU, severe WL, SU of any grade, DD of grade 3 or severe SH with moderate Se (between 0.40 and 0.60), which were lower than those obtained by HMS_BIN for all foot lesion types except DD. Since we excluded cases with concomitant severe lesions to calculate the actual negatives for each lesion, this led to the production of the same Sp across all lesions, which can be interpreted as an overall Sp of human or automated mobility scoring to accurately detect any of these lesions. We should note that the system's Se in detecting DD grade 3 was higher than that of the human scorer. This implies that humans fail to detect the potentially abnormal gait of cows with painful active DD lesions by a single mobility assessment. The improved performance of AIMS_BIN could be attributed to the weekly average score's ability to detect the dynamic alterations in cow's gait over a week's course without the presence of a human interfering with the normal walk of the affected cows. This is especially important for younger cows where DD is more prevalent (Smits et al., 1992; Somers et al., 2005) and which have a shorter flight distance and are more likely to exhibit fleeing behaviour even in pain when a human is present (Phillips, 2002).

When using mAVG, mMAX, mMIN and mPLS as parameters to describe the individual mobility pattern up to 30 days prior to trimming, we found that they provided improved measures of accuracy compared to AIMS_BIN for all lesions except TU. For TU, there were only 6 actual positive cases in the dataset, and none of the parameters could correctly discriminate them. In detecting severe SH and SU of any grade, mMIN had the best Se and mMAX had the best Sp. Most parameters showed adequate Se in detecting severe WL, with mMAX producing the best Se/Sp/Acc combination. Lastly, in detecting DD grade 3, all tested parameters showed similar discrimination, with mMAX and mPLS having the best Se and

mAVG having the best Sp. When looking at these parameters combined, the system could outperform the human scorer much the same as with the detection of moderate and of severe lesions previously described. With these results, it becomes clear that analysing the mobility patterns in cows with foot lesions and even using this data to train the algorithm for early detection of lesion development is necessary.

The longitudinal study was performed on a single farm but provided useful insights into the temporal dynamics of automated mobility scores in cows that developed lesions during the early lactation stage. The examination of the hind feet of the enrolled cows within the first 4 to 10 DIM ensured a known history for each cow around calving and gave us the possibility to account for the presence of pre-existing lesions that would affect mobility as we progress into lactation. By tracking the daily automated mobility scores from 5 to 64 DIM we were able to detect changes in what could be considered as a new phenotype for cattle lameness research and herd health management, the automated daily mobility score pattern of a cow. Our results showed that cows that were diagnosed with severe and even with moderate lesions at the early lactation foot trim, had higher scores throughout the first two months of lactation and a notably greater day-to-day variation. Cows with severe lesions had higher scores that were clearly separated from as early as 36 DIM from cows with moderate and with mild lesions, indicating the potential to identify earlier cows at higher risk to develop severe foot pathologies during early lactation. Even when we performed the same analysis but focused only on cows that developed sole lesions, collectively referring to SH and SU, we observed a tendency for higher scores across the first two months after calving. The incidence of sole lesions, peaks at three to five months of lactation (Leach et al., 1997; Barker et al., 2009). These findings indicate the importance of carrying out a first routine trim early into lactation, as the associated changes in mobility occurred before 40 DIM in the study herds enrolled. Detecting these changes could

help identify higher risk cows for an early lactation routine trim, while leaving those with good mobility for later. Research has indicated that a targeted early lactation intervention on heifers is cost beneficial over trimming all lame and non-lame heifers (Maxwell et al., 2015), and that foot trimming cows with good mobility induces stress leading to short-term decrease in activity, rumination, and milk production (Van Hertem et al., 2014). The efficacy of the system in detecting animals at risk of early-stage lesions, and the potential benefit derived from intervening in these animals warrants further investigation.

Moreover, a remark should be made about the increased scores and variability of cows with severe and with moderate lesions compared to those with no or mild lesions observed during the first 5 to 10 DIM: pathological, systemic inflammation around calving could be a valid explanation. Sole lesions are understood to occur because of inflammation and deranged horn production caused by a biomechanical insult applied to keratinocytes within the corium (Bergsten, 1994). However, systemic inflammation could also act as the initial trigger for the development of claw horn disruption lesions by disrupting blood circulation inside the corium and driving change to the functional anatomy of the foot (Watson et al., 2022; Wilson et al., 2022). Identifying cows undergoing pathological systemic inflammation immediately after calving just from the mobility pattern would be an interesting field for further research.

Guided by the results we obtained from this longitudinal study, we looked into PriorDATA2, which included cows that were trimmed between 60 and 120 DIM. We then conducted the same analysis to assess whether these findings can be replicated in a larger sample size of cows from multiple farms. We still observed increased mobility scores during the first 60 DIM in cows with severe lesions, with differences being most apparent towards the end of this period. We were unable to confirm the differences observed shortly after calving in the longitudinal study. The fact that we did not have a known history for these cows is a

733 limitation, although lesion status immediately after calving was not significantly associated
734 with the evolution of mobility scores in the longitudinal study.
735
736 Using PriorDATA1, we observed that cows with severe lesions regardless of the stage of
737 lactation had higher automated mobility scores from as early as 23 days before the trimming
738 session. This indicates that the system's daily scores can provide early warnings for potential
739 severe cases of lameness. Even when combining moderate and severe cases and comparing
740 them to mild ones, this separation was still noticeable. The ability for early detection is essential
741 for any lameness management protocol and if accompanied by timely and proper intervention,
742 it could be a valuable tool in our efforts to control lameness and improve overall herd health
743 and increase farm profitability. It has been shown that farmers are commonly underestimating
744 the lameness prevalence in their herds and recognize milder, and even severe cases with a
745 significant delay (Alawneh et al., 2012; Leach et al., 2012). Early detection and intervention
746 are crucial in preventing the development of severe pathologies, promoting recovery and
747 reducing recurrent cases (Leach et al., 2012; Groenevelt et al., 2014). The system's capacity to
748 provide regular and frequent mobility scores provides a substantial advantage over the farmer's
749 observations or even the human-conducted mobility score assessment, as it minimizes the
750 chances of missing early signs of lameness that might be overlooked in less frequent, or
751 inconsistent assessments of lameness.
752 We also highlighted the farm and parity effects on the daily scores, meaning that farm-
753 and parity-specific adjustments may improve the algorithm's accuracy and reliability.
754 Primiparous cows had lower mobility scores than older cows. Whether this is because
755 primiparous cows have a lower lameness prevalence or because they manifest pain and
756 lameness differently, remains unclear. Both seem plausible, the latter assumption though is
757 corroborated by the lower thresholds identified from ROC analysis to predict foot lesions in

758 primiparous cows. More data from longitudinal observations is required to address this issue.
759 Optimizing the system's performance across different environments and herd demographics is
760 a goal for future improvements. Artificial intelligence applications can handle complex data
761 and learn from experience without being programmed to and without compromising overall
762 accuracy (Sarker, 2021).
763
764 **Limitations**
765 The present study has some limitations that need to be acknowledged. Although the study
766 involved four experienced and trained researchers it did not assess intra-observer variability.
767 Including more observers with different backgrounds and levels of experience, would allow
768 for a more rigorous assessment of the inter-observer agreement between humans and make the
769 study more representative of how human mobility scoring is performed in practice. The study
770 was conducted on eleven commercial dairy farms housing in total more than 15,000 milking
771 cows which renders generalizability of our findings to intensively managed high-yielding
772 Holstein cows. However, the fact that some of the same farms were also used for training the
773 algorithm could be considered as a limitation. Nonetheless, since mobility, herd demographics
774 and environmental conditions are dynamic and we obtained similar results across farms, we
775 consider this issue to have a minimum influence on our findings. Furthermore, the fact that a
776 trained researcher collected the foot lesions data from a large number of cows is a strength of
777 our study. Although these data were collected during routine and therapeutic trims, the random
778 selection of several cows on each of the participating farms for foot inspection could provide
779 more reliable results on the system's accuracy in detecting cows with foot lesions. Lastly, the
780 longitudinal study was conducted on a single farm and the fact that foot trimming history for
781 cows with daily mobility scores was unknown, offers indicative findings, but does not allow
782 us to draw definite conclusions.

Conclusions

The automated 2-dimensional imaging system tested in this study demonstrated substantial agreement with human mobility scoring according to Gwet's agreement estimates, providing reliable detection of lame cows and cows with foot lesions across various dairy farms. The system showed sensitivity and specificity in detecting foot lesions comparable to those of a well-trained human assessor. Its capability to score cows frequently, consistently and unobtrusively providing daily mobility scores offered an advantage over the human assessor in terms of sensitivity. Moreover, we highlighted the system's potential for early intervention. Adoption of this system under a lameness management protocol could be useful in selecting cows for foot trimming, reducing lameness prevalence, preventing the development of severe lesions and improving overall health and welfare of dairy cows.

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1024

1025 **Table 1**. Overall inter-observer categorical agreement between the weekly average scores provided by an automated system (CE) and the visual mobility
1026 scores assigned by 4 experienced human assessors (HA) in 11 commercial dairy farms. Agreement on the four-grade scale (0/1/2/3) was estimated by
1027 calculating the quadratically weighted Cohen's kappa (κ_w) and the quadratically weighted Gwet's agreement coefficient (AC_2) with 95% confidence
1028 intervals shown in parentheses. Agreement on the binary converted two-grade scale (0,1/2,3) was estimated by calculating the percentage agreement (PA),
1029 unweighted Cohen's kappa (κ) and the unweighted Gwet's agreement coefficient (AC_1) with 95% confidence intervals shown in parentheses.

1030

	CE vs. HA1 n = 28,225			CE vs. HA2 n = 7,225			CE vs. HA3 n = 3,466			CE vs. HA4 1,200		
	PA	κ/κ_w	AC_1/AC_2	PA	κ/κ_w	AC_1/AC_2	PA	κ/κ_w	AC_1/AC_2	PA	κ/κ_w	AC_1/AC_2
0,1/2,3	83.7	0.38 (0.37-0.40)	0.78 (0.77-0.79)	81.5	0.23 (0.20-0.26)	0.76 (0.75-0.77)	82.1	0.32 (028-0.36)	0.76 (0.74-078)	86.3	0.34 (0.26-0.42)	0.83 (0.80-0.85)
0/1/2/3		0.34 (0.33-0.35)	0.86 (0.86-0.87)		0.33 (0.31-0.35)	0.85 (0.85-0.86)		0.24 (0.21-0.27)	0.81 (0.80-0.82)		0.26 (0.20-0.33)	0.93 (0.92-0.94)

1032 **Table 2.** Inter-observer agreement between two trained human assessors (HA1 and HA2)
1033 mobility scoring cows on the same day in one of the participating farms using the 0-3
1034 four-grade UK AHDB mobility scoring system. Agreement on the four-grade scale
1035 (0/1/2/3) was estimated by calculating the quadratically weighted Cohen's kappa (κ_w) and
1036 the quadratically weighted Gwet's agreement coefficient (AC_2) with 95% confidence
1037 intervals shown in parentheses. Agreement on the binary converted two-grade scale
1038 (0,1/2,3) was estimated by calculating the percentage agreement (PA), unweighted
1039 Cohen's kappa (κ) and the unweighted Gwet's agreement coefficient (AC_1) with 95%
1040 confidence intervals shown in parentheses.
1041
1042

		HA1 vs. HA2		
Farm	n	PA	κ/κ_w	AC_1/AC_2
D				
0,1/2,3	705	76.7	0.27 (0.19-0.35)	0.67 (0.61-0.72)
0/1/2/3			0.27 (0.21-0.33)	0.75 (0.72-0.78)

1043

1045 **Table 3**. Total number and percentage of foot lesions and severity grading recorded by a trained
1046 veterinarian during 61 foot trimming sessions, including routine and therapeutic trims,
1047 performed by professional foot trimmers in five of the participating farms.

1048

Lesion and grade of severity	N[1]	%
Sole haemorrhage		
1	743	29.5
2	494	19.6
3	280	11.1
Sole ulcer		
1	83	3.3
2	18	0.7
3	3	0.1
White line		
1	448	17.8
2	354	14.1
3	189	7.5
Axial wall fissure		
1	9	0.4
2	9	0.4
3	7	0.3
Toe ulcer		
1	1	0.0
2	7	0.3
3	3	0.1
Interdigital hyperplasia		
1	41	1.6
2	34	1.4
3	4	0.2
Interdigital phlegmon		
1	7	0.3
2	4	0.2
Digital dermatitis		
1	132	5.2
2	85	3.4
3	113	4.5

1049

1051 **Table 4**. Overall and per parity measures of accuracy (Sensitivity, Se; Specificity, Sp;
1052 Accuracy, Acc) for the binary converted human mobility scores (scores 2 and 3 on the 0-3 four-
1053 grade scale) and for the binary converted weekly average automated mobility scores (scores ≥
1054 50) in correctly detecting cows bearing at least one case of moderate and severe foot lesions
1055 using the recordings from a trained veterinarian as ground truth. The exact Clopper-Pearson
1056 binomial 95% confidence intervals (CI) are shown in parentheses.

1057

		Moderate and Severe			Severe		
	N[1]	Se (95% CI)	Sp (95% CI)	Acc (95% CI)	Se (95% CI)	Sp (95% CI)	Acc (95% CI)
Human mobility scores (≥ 2)							
Overall	758	0.38 (0.33-0.44)	0.84 (0.80-0.87)	0.62 (0.58-0.65)	0.60 (0.50-0.70)	0.78 (0.75-0.81)	0.76 (0.73-0.79)
Parity 1	247	0.21 (0.14-0.30)	0.94 (0.89-0.97)	0.62 (0.56-0.68)	0.33 (0.15-0.57)	0.89 (0.85-0.93)	0.85 (0.80-0.89)
Parity 2	154	0.32 (0.20-0.45)	0.86 (0.77-0.92)	0.66 (0.58-0.73)	0.62 (0.32-0.86)	0.83 (0.76-0.89)	0.81 (0.74-0.87)
Parity 3	160	0.38 (0.27-0.50)	0.76 (0.66-0.85)	0.58 (0.50-0.66)	0.60 (0.41-0.77)	0.76 (0.68-0.83)	0.73 (0.66-0.80)
Parity 4+	178	0.58 (0.49-0.67)	0.67 (0.54-0.79)	0.61 (0.54-0.68)	0.75 (0.58-0.88)	0.57 (0.59-0.65)	0.61 (0.53-0.68)
Weekly average automated mobility scores (≥ 50)							
Overall	2,515	0.37 (0.34-0.39)	0.76 (0.73-0.78)	0.58 (0.56-0.60)	0.53 (0.47-0.58)	0.74 (0.72-0.76)	0.71 (0.69-0.73)
Parity 1	440	0.12 (0.07-0.17)	0.94 (0.90-0.97)	0.61 (0.57-0.66)	0.26 (0.12-0.45)	0.93 (0.90-0 .95)	0.88 (0.85-0.91)
Parity 2	437	0.24 (0.18-0.32)	0.85 (0.80-0.89)	0.63 (0.59-0.68)	0.41 (0.25-0.58)	0.84 (0.80-0.87)	0.80 (0.76-0.84
Parity 3	820	0.42 (0.37-0.48)	0.71 (0.67-0.75)	0.59 (0.56-0.63)	0.60 (0.50-0.68)	0.70 (0.66-0.73)	0.68 (0.65-0.72)
Parity 4+	797	0.46 (0.41-0.51)	0.60 (0.55-0.65)	0.52 (0.49-0.56)	0.56 (0.48-0.65)	0.59 (0.56-0.63)	0.59 (0.55-0.62)

1058

1059 [1]N: number of cows

1060

Table 5. Measures of accuracy (Sensitivity, Se; Specificity, Sp; Accuracy, Acc) for the binary converted human mobility scores (scores 2 and 3 on the 0-3 four-grade scale) and for the binary converted weekly average automated mobility scores (scores ≥ 50) in correctly predicting the presence of specific foot lesions, using the recordings from a trained veterinarian as ground truth. The exact Clopper-Pearson binomial 95% confidence intervals (CI) are shown in parentheses.

	Human mobility scores (≥ 2)				Weekly average automated mobility scores (≥ 50)			
	N[1]	Se (95% CI)	Sp (95% CI)	Acc (95% CI)	N[1]	Se (95% CI)	Sp (95% CI)	Acc (95% CI)
Sole haemorrhage (Grade 3)	87/661	0.49 (0.39-0.60)	0.81 (0.77-0.84)	0.77 (0.73-0.80)	280/2,208	0.40 (0.35-0.46)	0.75 (0.73-0.77)	0.70 (0.68-0.72)
Sole ulcer (Grade ≥ 1)	38/612	0.63 (0.46-0.78)	0.81 (0.77-0.84)	0.80 (0.76-0.83)	104/2,032	0.52 (0.42-0.62)	0.75 (0.73-0.77)	0.74 (0.72-0.75)
White line (Grade 3)	55/629	0.67 (0.53-0.79)	0.81 (0.77-0.84)	0.80 (0.76-0.83)	196/2,124	0.55 (0.47-0.62)	0.75 (0.73-0.77)	0.73 (0.71-0.75)
Toe ulcer (Grade ≥ 1)	5/579	1.00 (0.48-1.00)	0.81 (0.77-0.84)	0.81 (0.78-0.84)	11/1,939	0.64 (0.31-0.89)	0.75 (0.73-0.77)	0.75 (0.73-0.77)
Digital dermatitis (Grade 3)	34/608	0.38 (0.22-0.56)	0.81 (0.77-0.84)	0.79 (0.75-0.82)	113/2,041	0.50 (0.40-0.59)	0.75 (0.73-0.77)	0.74 (0.71-0.75)

[1]N: number of actual positive cows / number of total cows eligible, after excluding cases with concomitant severe lesions.

1069 **Table 6.** Overall and per parity measures of accuracy (Sensitivity, Se; Specificity, Sp; Accuracy, Acc) for optimal thresholds, derived from receiver
1070 operating characteristic curves, for the average (mAVG), maximum (mMAX), minimum (mMIN) and percentage of scores that a cow was scored
1071 as lame (mPLS) during the past 30 days before foot trimming in 1,986 cows of five dairy farms, in correctly detecting cows bearing at least one
1072 case of moderate and severe foot lesions using the recordings from a trained veterinarian as ground truth. The exact Clopper-Pearson binomial
1073 95% confidence intervals (CI) for Se, Sp and Acc are shown in parentheses.
1074

	Moderate and Severe						Severe					
	Cut-off	AUC[1] (95% CI)	*P*-value	Se	Sp	Acc	Cut-off	AUC (95% CI)	*P*-value	Se	Sp	Acc
Overall, n[2] = 837/1,986							Overall, n = 228/1,986					
mAVG	44.5	0.58 (0.56 – 0.61)	< 0.001	0.44 (0.40-0.47)	0.70 (0.67-0.73)	0.59 (0.57-0.62)	45.9	0.69 (0.65 – 0.73)	< 0.001	0.55 (0.48-0.61)	0.73 (0.71-0.75)	0.71 (0.69-0.73)
mMAX	58.5	0.60 (0.57 – 0.62)	< 0.001	0.41 (0.37-0.44)	0.77 (0.74-0.79)	0.62 (0.59-0.64)	57.5	0.73 (0.69 – 0.76)	< 0.001	0.65 (0.59-0.72)	0.70 (0.68-0.72)	0.69 (0.67-0.71)
mMIN	32.5	0.57 (0.54 – 0.60)	< 0.001	0.45 (0.42-0.49)	0.66 (0.63-0.69)	0.57 (0.55-0.59)	32.5	0.65 (0.61 – 0.69)	< 0.001	0.57 (0.50-0.64)	0.64 (0.61-0.66)	0.63 (0.61-0.65)
mPLS	21.2	0.58 (0.55 – 0.60)	< 0.001	0.48 (0.45-0.52)	0.64 (0.61-0.66)	0.57 0.55-0.59)	11.9	0.69 (0.65 – 0.72)	< 0.001	0.76 (0.70-0.82)	0.52 (0.50-0.55)	0.55 (0.53-0.57)
Parity 1, n = 142/348							Parity 1, n = 21/348					
mAVG	NA[3]	0.55 (0.49 – 0.61)	0.095	NA	NA	NA	37.0	0.64 (0.52 – 0.76)	0.029	0.71 (0.48-0.89)	0.58 (0.52-0.63)	0.59 (0.53-0.64)
mMAX	NA	0.54 (0.48 – 0.60)	0.192	NA	NA	NA	46.5	0.66 (0.54 – 0.77)	0.015	0.76 (0.43-0.85)	0.53 (0.50-0.61)	0.54 (0.51-0.61)
mMIN	NA	0.54 (0.48 – 0.60)	0.196	NA	NA	NA	NA	0.60 (0.47 – 0.73)	0.122	NA	NA	NA
mPLS	NA	0.51 (0.44 – 0.57)	0.860	NA	NA	NA	NA	0.61 (0.48 – 0.73)	0.102	NA	NA	NA
Parity 2, n = 125/367							Parity 2, n = 29/367					

mAVG	43.6	0.57 (0.51 – 0.63)	0.030	0.38 (0.29-0.47)	0.76 (0.70-0.81)	0.63 (0.58-0.68)	41.6	0.67 (0.57 – 0.77)	0.002	0.66 (0.46-0.82)	0.65 (0.60-0.71)	0.65 (0.60-0.70)
mMAX	56.5	0.61 (0.54 – 0.67)	0.001	0.41 (0.32-0.50)	0.78 (0.72-0.83)	0.65 (0.60-0.70)	54.5	0.72 (0.62 – 0.82)	< 0.001	0.72 (0.53-0.87)	0.69 (0.63-0.74)	0.69 (0.64-0.74)
mMIN	NA	0.53 (0.47 – 0.59)	0.333	NA	NA	NA	25.5	0.63 (0.52 – 0.73)	0.025	0.79 (0.60-0.92)	0.42 (0.36-0.47)	0.45 (0.40-0.50)
mPLS	17.0	0.59 (0.53 – 0.65)	0.004	0.44 (0.35-0.53)	0.73 (0.67-0.78)	0.63 (0.58-0.68)	21.8	0.69 (0.59 – 0.79)	0.001	0.66 (0.46-0.82)	0.73 (0.67-0.77)	0.72 (0.67-0.76)
Parity 3, n = 254/669							Parity 3, n = 88/669					
mAVG	40.8	0.56 (0.52 – 0.61)	0.009	0.66 (0.60-0.72)	0.44 (0.39-0.49)	0.52 (0.49-0.56)	46.0	0.68 (0.62 – 0.74)	< 0.001	0.58 (0.47-0.68)	0.70 (0.66-0.73)	0.68 (0.64-0.72)
mMAX	59.5	0.58 (0.54 – 0.63)	< 0.001	0.39 (0.33-0.45)	0.78 (0.74-0.82)	0.63 (0.59-0.67)	62.5	0.74 (0.68 – 0.80)	< 0.001	0.55 (0.44-0.65)	0.85 (0.81-0.87)	0.81 (0.77-0.84)
mMIN	29.5	0.56 (0.51 – 0.60)	0.013	0.67 (0.61-0.73)	0.43 (0.38-0.48)	0.52 (0.48-0.56)	29.5	0.62 (0.56 – 0.68)	< 0.001	0.77 (0.67-0.86)	0.41 (0.37-0.46)	0.46 (0.42-0.50)
mPLS	17.0	0.56 (0.51 – 0.60)	0.017	0.54 (0.48-0.60)	0.53 (0.48-0.58)	0.53 (0.50-0.57)	12.3	0.68 (0.62 – 0.74)	< 0.001	0.80 (0.70-0.87)	0.48 (0.44-0.52)	0.52 (0.48-0.56)
Parity 4+, n = 311/590							Parity 4+, n = 90/590					
mAVG	44.6	0.59 (0.55 – 0.64)	< 0.001	0.61 (0.55-0.66)	0.57 (0.51-0.63)	0.59 (0.55-0.63)	46.1	0.66 (0.59 – 0.72)	< 0.001	0.69 (0.58-0.78)	0.56 (0.51-0.60)	0.58 (0.54-0.62)
mMAX	58.5	0.62 (0.58 – 0.67)	< 0.001	0.53 (0.47-0.59)	0.70 (0.64-0.75)	0.61 (0.57-0.65)	57.5	0.70 (0.64 – 0.76)	< 0.001	0.73 (0.63-0.82)	0.59 (0.55-0.63)	0.61 (0.57-0.65)
mMIN	35.5	0.58 (0.54 – 0.63)	< 0.001	0.49 (0.43-0.54)	0.67 (0.62-0.73)	0.58 (0.53-0.61)	32.5	0.62 (0.56 – 0.69)	< 0.001	0.69 (0.58-0.78)	0.48 (0.44-0.53)	0.51 (0.47-0.56)
mPLS	38.2	0.58 (0.54 – 0.63)	0.001	0.49 (0.43-0.55)	0.66 (0.57-0.71)	0.57 (0.53-0.61)	41.6	0.65 (0.58 – 0.71)	< 0.001	0.58 (0.47-0.68)	0.63 (0.59-0.67)	0.63 (0.58-0.66)

1075

1076 [1]AUC: area under the curve

1077 [2]n: number of actual positive cows

1078 [3]NA: not applicable

1079

1080 **Table 7.** Overall and per parity measures of accuracy (Sensitivity, Se; Specificity, Sp;
1081 Accuracy, Acc) for optimal thresholds, derived from receiver operating characteristic curves,
1082 for the average (mAVG), maximum (mMAX), minimum (mMIN) and percentage of scores
1083 that a cow was scored as lame (mPLS) during the past 30 days before foot trimming in 1,986
1084 cows of five dairy farms, in correctly predicting the presence of specific foot lesions, using the
1085 recordings from a trained veterinarian as ground truth. The exact Clopper-Pearson binomial
1086 95% confidence intervals (CI) for Se, Sp and Acc are shown in parentheses.
1087

	Cut-off	AUC[1] (95% CI)	*P*-value	Se (95% CI)	Sp (95% CI)	Acc (95% CI)
Sole haemorrhage						
n^2 = 201/1,770						
mAVG	43.6	0.61 (0.57 – 0.66)	< 0.001	0.53 (0.46-0.60)	0.64 (0.62-0.67)	0.63 (0.61-0.65)
mMAX	64.5	0.60 (0.56 – 0.65)	< 0.001	0.28 (0.22-0.35)	0.89 (0.87-0.90)	0.82 (0.80-0.84)
mMIN	30.5	0.61 (0.57 – 0.65)	< 0.001	0.62 (0.55-0.68)	0.56 (0.54-0.59)	0.57 (0.54-0.59)
mPLS	35.5	0.59 (0.55 – 0.63)	< 0.001	0.41 (0.34-0.48)	0.75 (0.73-0.77)	0.71 (0.69-0.73)
Sole ulcer						
n = 69/1,638						
mAVG	47.3	0.69 (0.63 – 0.75)	< 0.001	0.51 (0.38-0.63)	0.78 (0.76-0.80)	0.77 (0.75-0.79)
mMAX	65.5	0.70 (0.63 – 0.76)	< 0.001	0.42 (0.30-0.55)	0.90 (0.89-0.92)	0.88 (0.87-0.90)
mMIN	29.5	0.68 (0.62 – 0.74)	< 0.001	0.77 (0.65-0.86)	0.51 (0.48-0.54)	0.52 (0.50-0.55)
mPLS	23.4	0.66 (0.59 – 0.73)	< 0.001	0.65 (0.53-0.76)	0.65 (0.62-0.67)	0.65 (0.62-0.67)
White line						
n = 129/1,698						
mAVG	43.5	0.72 (0.68 – 0.77)	< 0.001	0.70 (0.61-0.78)	0.64 (0.61-0.66)	0.64 (0.62-0.67)
mMAX	57.5	0.79 (0.74 – 0.83)	< 0.001	0.74 (0.65-0.81)	0.71 (0.68-0.73)	0.71 (0.69-0.73)
mMIN	30.5	0.67 (0.62 – 0.71)	< 0.001	0.69 (0.60-0.77)	0.56 (0.54-0.59)	0.57 (0.55-0.60)
mPLS	11.9	0.71 (0.67 – 0.76)	< 0.001	0.81 (0.74-0.88)	0.53 (0.51-0.56)	0.55 (0.53-0.58)
Toe ulcer						
n = 6/1,575						
mAVG	NA	0.61 (0.34 – 0.88)	0.371	NA	NA	NA
mMAX	NA	0.61	0.371	NA	NA	NA

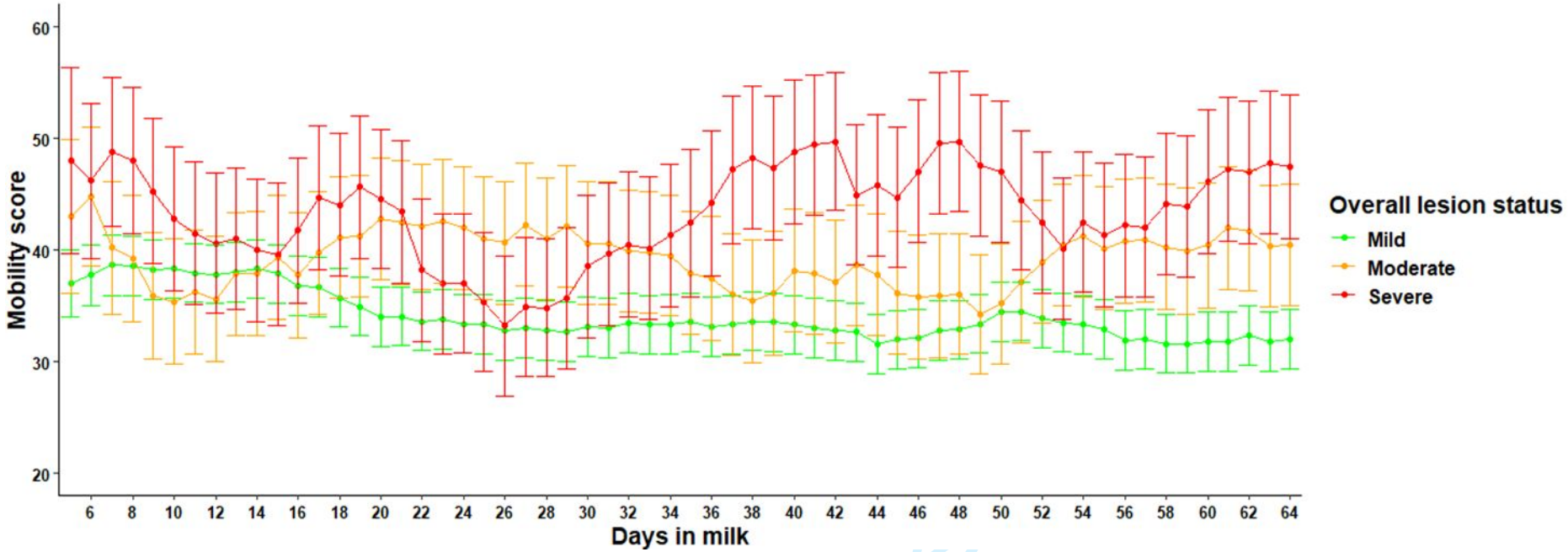
		(0.37 – 0.86)				
mMIN	NA	0.55 (0.27 – 0.84)	0.658	NA	NA	NA
mPLS	NA	0.56 (0.29 – 0.83)	0.608	NA	NA	NA
Digital dermatitis						
n = 83/1,652						
mAVG	46.0	0.66 (0.60 – 0.72)	< 0.001	0.52 (0.41-0.63)	0.74 (0.72-0.76)	0.73 (0.71-0.75)
mMAX	54.5	0.66 (0.60 – 0.72)	< 0.001	0.66 (0.55-0.76)	0.60 (0.58-0.63)	0.60 (0.58-0.63)
mMIN	32.5	0.63 (0.57 – 0.70)	< 0.001	0.57 (0.45-0.67)	0.65 (0.63-0.67)	0.65 (0.62-0.67)
mPLS	20.3	0.66 (0.60 – 0.72)	< 0.001	0.65 (0.54-0.75)	0.62 (0.60-0.64)	0.62 (0.60-0.65)

[1]AUC: area under the curve

[2]n: number of actual positive cows / number of total cows eligible, after excluding cases with concomitant severe lesions.

Figure 1.

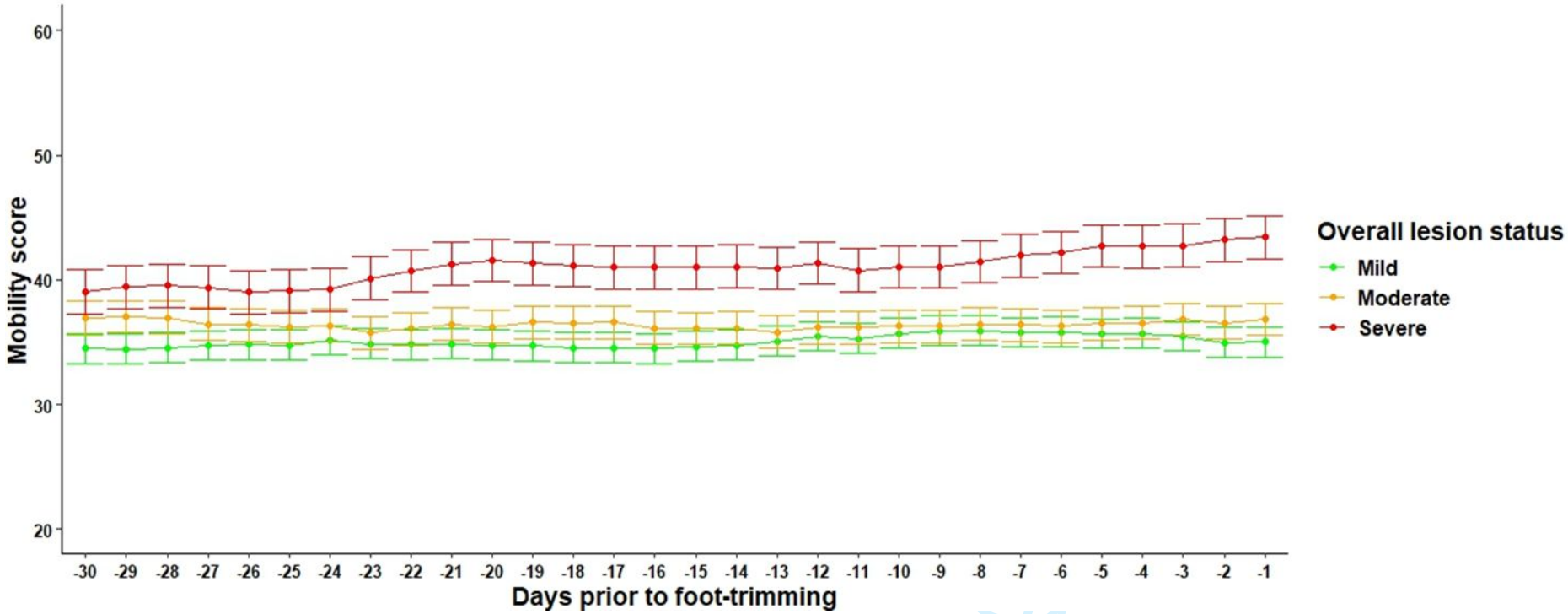
Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for the effect of parity and lesion status detected immediately after calving, showing the evolution of daily automated mobility scores tracked from 5 to 64 DIM in 143 cows classified in three levels according to the presence and severity of foot lesions identified during the early lactation foot trim, which was performed at a median of 94 DIM. A statistically significant association of the Overall lesion status × DIM interaction was observed ($P < 0.001$) with the daily mobility scores.


Mobility score
60
50
40
30
20
6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64
Days in milk
Overall lesion status
Mild
Moderate
Severe

1100

Figure 2.

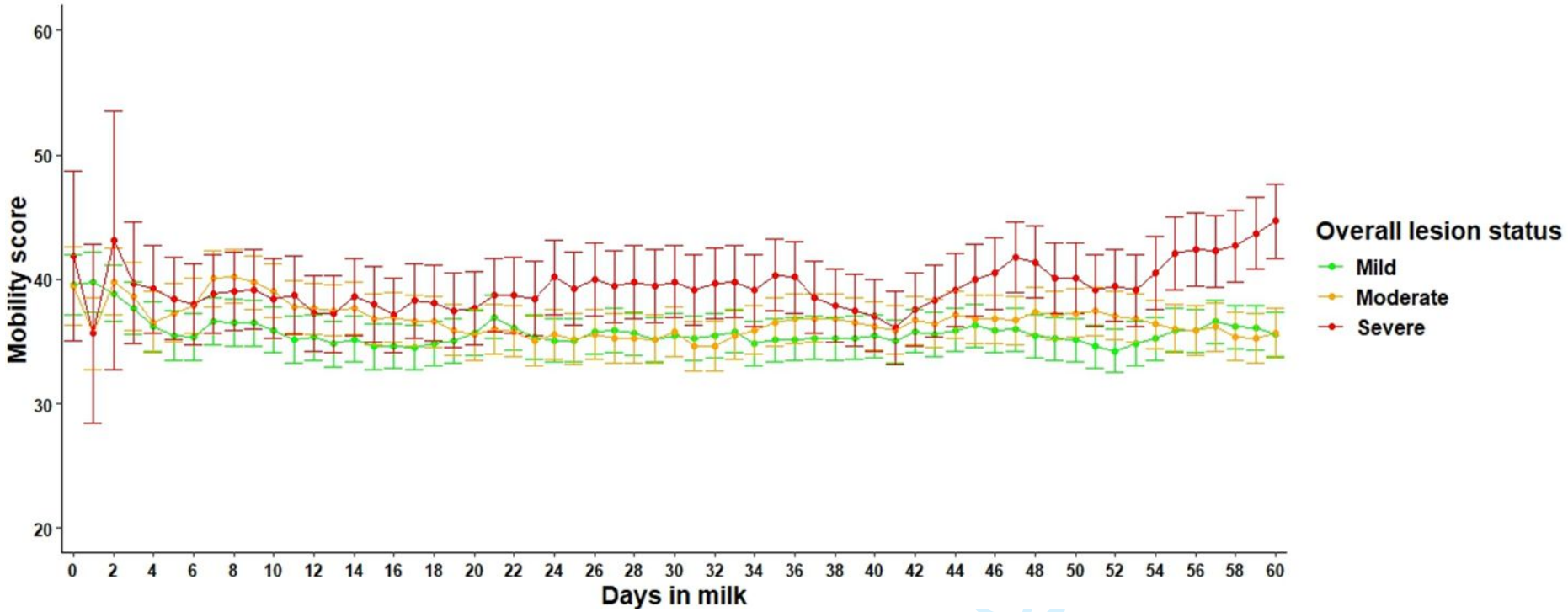
Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for farm and parity effects, showing the evolution of daily automated mobility scores tracked from 30 to 1 days before trimming (DBT) in 1,986 cows of five farms classified in three levels according to the presence and severity of foot lesions identified during the trimming session. A statistically significant association of the Overall lesion status ($P < 0.001$) and of the Overall lesion status × DBT interaction was observed ($P = 0.025$) with the historical mobility scores.


Mobility score
60
50
40
30
20
-30 -29 -28 -27 -26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1
Days prior to foot-trimming
Overall lesion status
Mild
Moderate
Severe

1107

Figure 3.

Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for farm and parity effects, showing the evolution of daily automated mobility scores tracked during the first 60 DIM in 615 cows of five farms that were trimmed between 60 and 120 DIM classified in three levels according to the presence and severity of foot lesions identified during the trimming session. A statistically significant association of the Overall lesion status ($P = 0.042$) and of the Overall lesion status × DIM interaction was observed ($P < 0.001$) with the historical mobility scores.


Mobility score
60
50
40
30
20
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
Days in milk
Overall lesion status
Mild
Moderate
Severe

1115

1116

Evaluation of a fully automated 2D imaging system for real-time cattle lameness detection using machine learning

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Supplemental Material

13 **Supplemental Table S1**. Case and severity definition for foot lesions recorded in the present study.

14

Grade	0	1	2	3
Sole Haemorrhage (SH)	Absence of lesion	Lesion smaller than 2 cm light pink in colour	Lesion wider than 2 cm in diameter of light pink coloration or dark red coloured lesion smaller than 2 cm	Dark red coloured lesion wider than 2 cm or blue coloured lesion of any size
Sole Ulcer (SU)	Absence of lesion	Small ulceration with less than 2cm diameter	Ulceration 2 cm in diameter or wider and/or soft tissue less than 1.5 cm in size protruding through the horn	Soft tissue larger than 1.5 cm is exposed protruding through the horn and/or secondary infection and necrosis is present and/or fistulas or abscess present
White Line (WL)	Absence of lesion	Mild discoloration, haemorrhage or separation is observed on the white line that is not visible after trimming	Deep separation or discoloration of the white line. The discoloration is still present after trimming with a knife and soft tissue might be exposed if excision is attempted	Fissure, with the corium involved and/or purulent exudate or necrosis. Fistulas might be found connecting the lesion to the coronary band or underrunning the sole
Axial wall fissure (AWF)	Absence of lesion	A thin fissure is observed running through the axial wall and cannot be spotted after the modelling	The fissure is still present after the modelling and soft tissue might be exposed if excision is attempted	Purulent exudate is leaking through the fissure, fistulas or tracks can be spotted
Toe Ulcer (TU)	Absence of lesion	Small ulceration with less than 2cm diameter	Ulceration 2 cm in diameter or wider and/or soft tissue less than 1.5 cm in size protruding through the horn	Soft tissue larger than 1.5 cm is exposed protruding through the horn and/or secondary infection and toe necrosis is present and/or abscess present
Interdigital Hyperplasia (IH)	Absence of lesion	Fibrous tissue flap on the interdigital skin that does not increase the distance between claws	The claw distance is increased due to the growth of the interdigital fibrous tissue.	The interdigital growth increases the distance between claws and shows signs of inflammation and/or traumatic bleeding

Interdigital phlegmon (IP)	Absence of lesion	Swelling of the digits up to the fetlock	Tissue between coronary band and fetlock broken open with a foul odour. Fistulas can be found in the interdigital space	NA
Digital Dermatitis (DD)	Absence of lesion	M4 and M3 stages of digital dermatitis	M4.1 and M1 stages of digital dermatitis	M2 stage of digital dermatitis

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Supplemental Table S2. Dataset used to estimate the categorical agreement between the human mobility scoring (HMS), performed by 4 experienced human assessors (HA), and the weekly average automated mobility scores (AIMS) in 11 dairy farms with a milking herd size ranging from approximately 600 to 2,800 Holstein cows, showing the number of cows scored per session and per farm and the lameness prevalence recorded on each session by the HA and the system.

Farm	Scorer	Visit order per farm	No. of cows	Prevalence HMS	Prevalence AIMS
A	HA2	1	878	0.190	0.058
	HA2	2	855	0.202	0.068
	HA1	3	905	0.136	0.062
	HA1	4	955	0.185	0.081
B	HA2	1	1,937	0.131	0.060
	HA1	2	1,842	0.116	0.056
	HA1	3	1,832	0.148	0.110
C	HA2	1	561	0.152	0.121
	HA3	2	644	0.146	0.172
	HA1	3	475	0.160	0.255
	HA1	4	544	0.160	0.193
	HA1	5	583	0.194	0.261
D	HA2	1	1,693	0.243	0.019
	HA3	2	1,482	0.155	0.162
	HA1	3	1,710	0.149	0.114

	HA1	4	1,801	0.202	0.107
	HA1	5	694	0.219	0.287
	HA1	6	711	0.200	0.295
	HA1	7	732	0.235	0.291
	HA1	8	727	0.242	0.260
	HA1	9	732	0.239	0.298
	HA1	10	1,319	0.269	0.249
	HA1	11	730	0.275	0.256
	HA1	12	743	0.206	0.271
E	HA4	1	491	0.118	0.073
	HA2	2	619	0.247	0.121
	HA3	3	621	0.143	0.114
	HA1	4	615	0.231	0.127
	HA1	5	597	0.291	0.124
F	HA4	1	709	0.159	0.104
	HA2	2	682	0.302	0.132
	HA3	3	719	0.145	0.200
	HA1	4	693	0.101	0.163
	HA1	5	659	0.185	0.185
	HA1	6	655	0.197	0.220
G	HA1	1	517	0.101	0.062
	HA1	2	578	0.102	0.085
H	HA1	1	1,050	0.095	0.098
	HA1	2	1,608	0.154	0.114
I	HA1	1	1,269	0.104	0.051

J	HA1	1	566	0.191	0.097
K	HA1	1	2,384	0.071	0.055

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Supplemental Table S3. Inter-observer categorical agreement between the weekly average scores provided by an automated system (CE) and the visual mobility scores assigned by 4 experienced human assessors (HA) in 11 commercial dairy farms. Agreement on the four-grade scale (0/1/2/3) was estimated by calculating the quadratically weighted Cohen's kappa (κ_w) and the quadratically weighted Gwet's agreement coefficient (AC_2) with 95% confidence intervals shown in parentheses. Agreement on the binary converted two-grade scale (0,1/2,3) was estimated by calculating the percentage agreement (PA), unweighted Cohen's kappa (κ) and the unweighted Gwet's agreement coefficient (AC_1) with 95% confidence intervals shown in parentheses.

	CE vs. HA1				CE vs. HA2				CE vs. HA3				CE vs. HA4			
Farm	n	PA	κ/κ_w	AC_1/AC_2	n	PA	κ/κ_w	AC_1/AC_2	n	PA	κ/κ_w	AC_1/AC_2	n	PA	κ/κ_w	AC_1/AC_2
A	1,860				1,733											
0,1/2,3		86.3	0.35 (0.29-0.41)	0.83 (0.81-0.85)		83.3	0.29 (0.23-0.35)	0.78 (0.76-0.81)								
0/1/2/3			0.31 (0.27-0.34)	0.88 (0.87-0.89)			0.33 (0.29-0.37)	0.88 (0.88-0.89)								
B	3,373				1,937											
0,1/2,3		90.0	0.48 (0.44-0.53)	0.88 (0.86-0.89)		86.5	0.29 (0.23-0.35)	0.84 (0.82-0.86)								
0/1/2/3			0.37 (0.34-0.40)	0.87 (0.86-0.88)			0.29 (0.24-0.33)	0.84 (0.83-0.85)								
C	1,602				561				644							
0,1/2,3		81.8	0.44 (0.39-0.49)	0.73 (0.70-0.76)		83.4	0.30 (0.19-0.41)	0.78 (0.74-0.83)		86.2	0.48 (0.39-0.58)	0.81 (0.77-0.85)				
0/1/2/3			0.44	0.83			0.36	0.83			0.38	0.80				

			(0.40-0.47)	(0.82-0.84)			(0.29-0.43)	(0.81-0.85)			(0.32-0.44)	(0.78-0.83)				
D	9,899				1,693				1,482							
0,1/2,3		78.1	0.35 (0.33-0.37)	0.67 (0.65-0.68)		77.0	0.09 (0.05-0.13)	0.70 (0.67-0.74)		78.1	0.18 (0.12-0.24)	0.70 (0.67-0.74)				
0/1/2/3			0.29 (0.28-0.31)	0.87 (0.87-0.87)			0.22 (0.18-0.26)	0.87 (0.86-0.88)			0.12 (0.08-0.16)	0.81 (0.80-0.83)				
E	1,212				619				621				491			
0,1/2,3		80.0	0.38 (0.32-0.44)	0.71 (0.67-0.75)		77.4	0.27 (0.18-0.35)	0.68 (0.62-0.73)		86.2	0.38 (0.28-0.49)	0.82 (0.78-0.86)		89.0	0.37 (0.24-0.50)	0.87 (0.83-0.90)
0/1/2/3			0.32 (0.28-0.37)	0.82 (0.81-0.84)			0.28 (0.22-0.35)	0.86 (0.84-0.88)			0.25 (0.19-0.31)	0.81 (0.80-0.83)			0.26 (0.16-0.36)	0.93 (0.92-0.94)
F	2,007				682				719				709			
0,1/2,3		84.8	0.47 (0.42-0.52)	0.79 (0.76-0.81)		75.7	0.31 (0.24-0.39)	0.63 (0.57-0.69)		83.0	0.41 (0.32-0.50)	0.76 (0.72-0.81)		84.3	0.32 (0.22-0.42)	0.80 (0.76-0.84)
0/1/2/3			0.38 (0.34-0.42)	0.86 (0.85-0.87)			0.35 (0.28-0.41)	0.87 (0.85-0.88)			0.30 (0.24-0.37)	0.81 (0.78-0.83)			0.26 (0.19-0.34)	0.93 (0.92-0.94)
G	1,095															
0,1/2,3		89.2	0.33 (0.24-0.42)	0.87 (0.85-0.90)												
0/1/2/3			0.28 (0.23-0.34)	0.85 (0.84-0.86)												
H	2,658															
0,1/2,3		84.5	0.27 (0.22-0.32)	0.80 (0.78-0.82)												
0/1/2/3			0.20	0.87												

			(0.17-0.24)	(0.86-0.88)											
I	1,269														
0,1/2,3		89.0	0.24 (0.16-0.33)	0.87 (0.85-0.89)											
0/1/2/3			0.29 (0.24-0.34)	0.87 (0.86-0.88)											
J	566														
0,1/2,3		83.9	0.36 (0.26-0.46)	0.79 (0.74-0.83)											
0/1/2/3			0.42 (0.36-0.49)	0.87 (0.86-0.89)											
K	2,379														
0,1/2,3		91.3	0.26 (0.19-0.33)	0.90 (0.89-0.92)											
0/1/2/3			0.24 (0.21-0.28)	0.87 (0.87-0.88)											
All	28,225				7,225				3,466				1,200		
0,1/2,3		83.7	0.38 (0.37-0.40)	0.78 (0.77-0.79)		81.5	0.23 (0.20-0.26)	0.76 (0.75-0.77)		82.1	0.32 (028-0.36)	0.76 (0.74-078)		86.3	0.34 (0.26-0.42)	0.83 (0.80-0.85)
0/1/2/3			0.34 (0.33-0.35)	0.86 (0.86-0.87)			0.33 (0.31-0.35)	0.85 (0.85-0.86)			0.24 (0.21-0.27)	0.81 (0.80-0.82)			0.26 (0.20-0.33)	0.93 (0.92-0.94)

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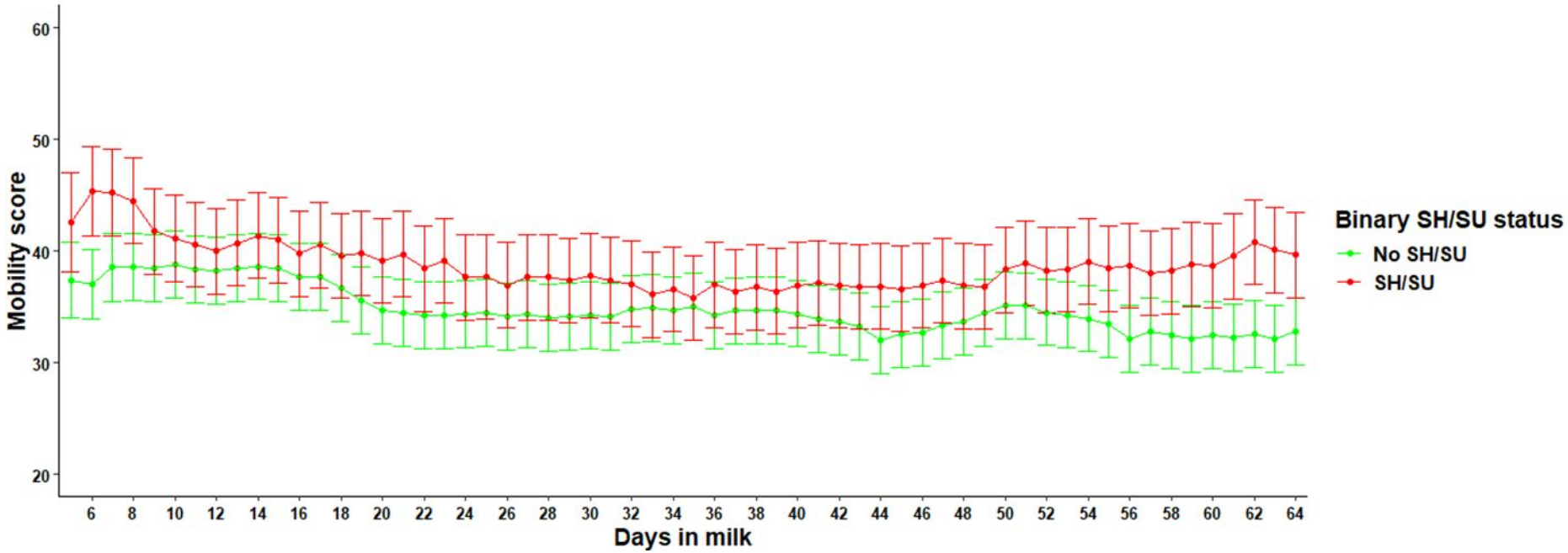
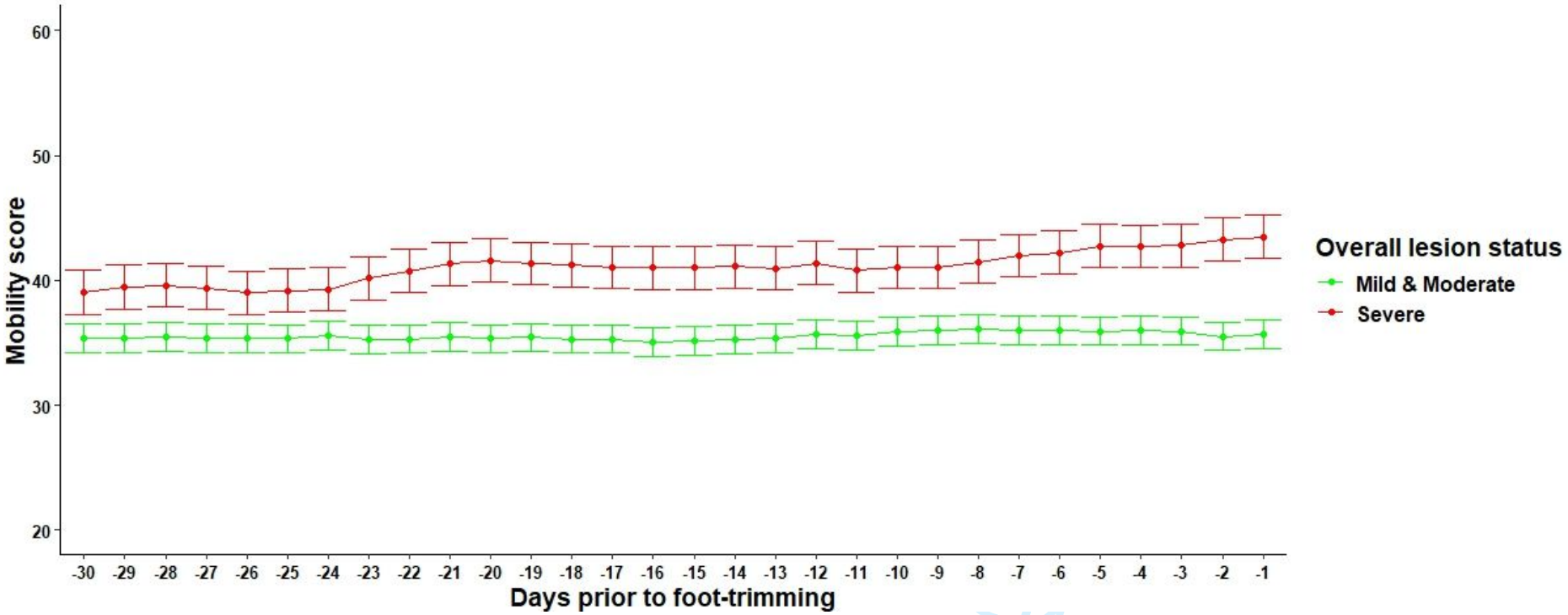
Supplemental Figure S1.

Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for the effect of parity and lesion status detected immediately after calving, showing the evolution of daily automated mobility scores tracked from 5 to 64 DIM in 130 cows that were diagnosed during the early lactation routine trim with moderate or severe lesions other than SH grade ≥ 2 or SU of any grade. Cows were binary classified according to the SH/SU status. Binary SH/SU status showed a tendency for statistical significance ($P = 0.096$).



Supplemental Figure S2.

Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for farm and parity effects, showing the evolution of daily automated mobility scores tracked from 30 to 1 days before trimming (DBT) in 1,986 cows of five farms binary classified (mild and moderate vs. severe) according to the presence and severity of foot lesions identified during the trimming session. A statistically significant association of the Overall lesion status ($P < 0.001$) and of the Overall lesion status × DBT interaction was observed ($P < 0.001$) with the historical mobility scores.


Mobility score
60
50
40
30
20
-30 -29 -28 -27 -26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1
Days prior to foot-trimming
Overall lesion status
Mild & Moderate
Severe

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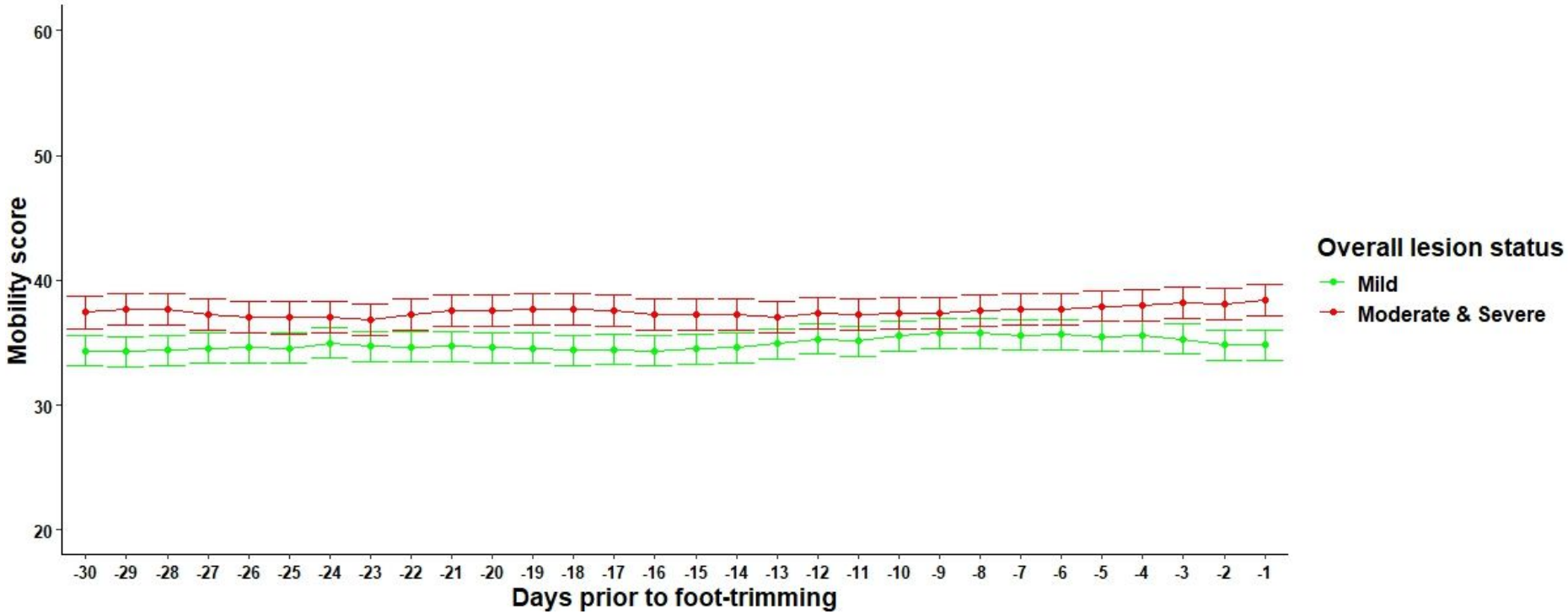
Supplemental Figure S3.

Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for farm and parity effects, showing the evolution of daily automated mobility scores tracked from 30 to 1 days before trimming (DBT) in 1,986 cows of five farms binary classified (mild vs. moderate and severe) according to the presence and severity of foot lesions identified during the trimming session. A statistically significant association of the Overall lesion status ($P < 0.001$) was observed with the historical mobility scores.



Supplemental Figure S4.

Estimated marginal means (± 95% confidence intervals) derived from linear mixed models accounting for farm and parity effects, showing the evolution of daily automated mobility scores tracked during the first 60 DIM in 615 cows of five farms that were trimmed between 60 and 120 DIM binary classified (mild and moderate vs. severe) according to the presence and severity of foot lesions identified during the trimming session. A statistically significant association of the Overall lesion status × DIM interaction was observed ($P < 0.001$) with the historical mobility scores.