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Spatial behaviour of dairy cows is affected by lameness

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ABSTRACT

Lameness is one of the major welfare problems on modern dairy farms, and additionally, it is difficult to control. Lameness is associated with changes in cow behaviour, and efforts have been made to automatically detect these behavioural changes. However, systems relying on a single behavioural variable are likely to fail. Indoor positioning could provide means to measure multiple behavioural variables with a single system. Our aim was to investigate how lameness affects the spatial behaviour of cows, measured with an indoor positioning system. In total, 71 lactating dairy cows were followed during a 7-month study period, with 48 cows in the study simultaneously. Cows were locomotion scored fortnightly with a 10-tier scale, and their daily time spent in the different functional areas of the barn, walking distance, and home range were calculated from the positioning data. Each locomotion score was merged with the 5-day average of the behaviour variables leading up to the scoring day, resulting in 376 observations in the final data. Linear mixed models were fitted with backwards stepwise elimination to test the associations between positioning-based daily behavioral variables and predictor variables comprising locomotion score, parity, lactation stage, breed and the proportion of missing positioning data. Increasing locomotion score was associated with increased time spent in the lying stalls ($P = 0.0037$) and decreased time spent in the alley ($P < 0.0001$). Positioning-based feeding time was confounded by parity ($P = 0.011$) as the model used to estimate the feeding time from the position data was less sensitive in classifying primiparous cows correctly as feeding or not feeding. Severe lameness was also associated with a shorter daily walking distance ($P = 0.0447$) and smaller core home range ($P = 0.005$). Proportion of missing positioning data affected only daily walking distance ($P < 0.0001$) and full home range ($P = 0.0059$), and distance-based variables seemed more sensitive to data quality compared to spatiotemporal variables. Our results show that indoor positioning of dairy cows has a potential to contribute to development of automatic lameness detection. However, reliability of positioning systems should be improved, and the amount of missing data should be minimised to improve the calculation of distance-based variables.

1. Introduction

Lameness in dairy cows causes significant economic losses to modern dairy farms (Bruijnis et al., 2010; Alvergnas et al., 2019), causes pain and has adverse effects on animal health and welfare (Whay and Shearer, 2017). The mean prevalence of lameness in Finnish loose housing systems is 23 %, ranging from 2 % to 62 % between farms (Sarjokari et al., 2013), whereas in e.g. North America it is 15 %, ranging from 2.5 % to 46 % (Westin et al., 2016a). Bruijnis et al. (2010) estimated that the annual loss caused by foot disorders is 66 € per cow, and 32 % of this sum arises from undetected and untreated lameness cases. The main factors causing these economic losses are reduced milk production and involuntary culling. Indeed, total losses in milk production can vary between 270 and 574 kg over a whole lactation period (Huxley, 2013). Other detrimental factors are treatment costs, additional management time, discarded milk and impaired fertility. Despite these facts, farmers often underestimate both the costs and the prevalence of lameness on their farm, and they also perceive lameness as more difficult to control than other health issues (Leach et al., 2010). Additionally, commonly used subjective methods for lameness detection are laborious and unreliable (Schlageter-Tello et al., 2014). Because of the high impact of lameness on farm economics and animal welfare, and the difficulties that farmers face detecting lame animals, research on automated lameness detection systems has increased.

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Association between lameness and daily behaviour of dairy cows is already well presented in literature (Van Nuffel et al., 2015a; Alsaaod et al., 2019). Lame cows spend less time feeding, have fewer feeding bouts, and eat faster compared to non-lame animals (González et al., 2008; Miguel-Pacheco et al., 2014; Thorup et al., 2016; Barker et al., 2018). Lame cows also have decreased standing time (Walker et al., 2008; Blackie et al., 2011), walking time (Walker et al., 2008; Thorup et al., 2015), and they visit the milking robot less frequently (Miguel--Pacheco et al., 2014). Therefore, lame cows increase their lying time (Thorup et al., 2015; Hut et al., 2021) and they tend to lie down close to the pen entrance after milking (Juarez et al., 2003). Measuring the activity and the lying time of the cows with accelerometers is already feasible on commercial farms. However, despite the evidence of the association between lameness and increased lying time, using lying time solely to detect lame animals is not a functioning option (O'Leary et al., 2020). On the other hand, automated measurements of feeding behaviour on commercial farms are still uncommon due to high cost of the measurement equipment (Stygar et al., 2021).

Indoor positioning systems, also referred to as real-time localisation systems, could be used to measure multiple behaviours of dairy cows with a single system. Positioning can accurately give an occupancy level of the different functional areas in the barn (Porto et al., 2014; Tullo et al., 2016; Melzer et al., 2021). For example, feeding time can be estimated based on the time spent in the feeding area (Shane et al., 2016; Pastell and Frondelius, 2018), or resting behaviour based on the lying area occupancy (Churakov et al., 2021). Even the use of brushes and mineral blocks (Meunier et al., 2018), or the social interactions between the cows (Ren et al., 2021a), can be extracted from the location data. Veissier et al. (2017) used the space use patterns of the cows to calculate an activity index to chart the circadian rhythm of the animals. However, it is necessary to bear in mind that location can be only an indirect measurement of these behaviours. Position data also gives an opportunity to measure the distance cows travel inside the barn (Frondelius et al., 2015) or the range of the area in which cows spent most of their time, also called home range (Vázquez Diosdado et al., 2018).

Although indoor positioning shows potential for measuring dairy cow behaviour, relatively few studies have tried to use positioning-based data to detect health issues. First studies analysing the position-based data in relation to lameness have shown that the circadian activity pattern (Veissier et al., 2017; Wagner et al., 2021), daily walking distance (Frondelius et al., 2015) and space-use patterns (Vázquez Diosdado et al., 2018) of dairy cows are affected by lameness. The aim of our study was to use indoor positioning of dairy cows to measure distance-based variables and the time spent in different functional areas of the barn, and to investigate how the time spent in lying stalls, alleys and roughage feeders is affected by a locomotion score based on a sum of frequently used lameness indicators present in a cow locomotion.

2. Materials and methods

2.1. Housing and management

The study was conducted in a research barn of the Natural Resources Institute Finland in Maaninka (63º 10 'N, 27º 18'E), from May to November 2015. The experimental animals comprised 71 lactating dairy cows during the whole study period, with 48 cows in the study at the same time. The cows were loose-housed in a curtain-wall barn in two compartments of 24 cows each. Slatted floors were automatically scraped (Lely Discovery 90SW, Lely, The Netherlands), and the alley next to the feed bunk was covered with a rubber mat. Compartments had fifteen 120 cm and nine 130 cm wide stalls with a total length of 250 cm and a body resting length of 180 cm from the brisket board. Cubicles were covered with mattresses (Promat Inc, Canada) and additional peat-bedding was used on top. Both compartments had their own concentrate feeder (Nedap Livestock Management, The Netherlands) and twelve Insentec Roughage Intake Control (RIC) feeders (Insentec BV, The Netherlands) with added barrier structures preventing stealing behaviour (Ruuska et al., 2014). The cows had free access to total mixed ratio, including grass silage with 45 % of concentrate (barley-rapeseed meal mixture 80:20) achieving 11.5 – 11.7 MJ/kg in dry matter. Fresh feed was delivered six times daily. Water was freely available. The cows were milked twice daily in a 2 × 8 herringbone parlour.

The cows were either primiparous (n = 28), second parity (n = 21) or multiparous (n = 22) and were either Holstein-Friesian (n = 41) or Nordic Red (n = 30) breeds. Parities were evenly distributed between the breeds. During the experiment, cows were between 11 and 297 days in milk (DIM), and their average daily milk yield was 29.6 ± 5.5 kg (mean ± standard deviation (SD)). As we wanted to study lactating dairy cows, we removed the animals from the experiment when they finished their lactation period and replaced them with new cows in early lactation stage. Thus, depending on their lactation stage, cows were in the experiment for 0.5–7 months. One cow enrolled in the experiment in its first lactation, was removed for dry period and re-entered the experiment in its second lactation.

This study design was reviewed and approved by Animal Welfare body (Government decree 564/2013 22§) of Natural Resources Institute Finland. Project authorization was not needed as the experiment did not cause the animals a level of pain, suffering, distress or lasting harm equivalent to, or higher than, that caused by the introduction of a needle (2010/63/EU).

2.2. Data collection

A Ubisense indoor positioning system (Ubisense Ltd, United Kingdom) was used to continuously monitor the location of all cows in the experiment with a sample rate of 1.2 Hz. The system is based on ultra-wide band (UWB) radio signals. A collar-mounted tag (Ubisense Series 7000 Industrial tag) transmits UWB pulses of extremely short duration, and UWB radio receivers (Ubisense Series 7000 IP Sensors) fixed at certain positions in the barn receive the signals and calculate the position of the tag using Time-Difference-of-Arrival (TDoA) and Angle-of-Arrival (AoA) methods. The positioning system was set up to cover both study compartments, in total an area of 22 × 25 m. The milking parlour was outside of this area. The setup of the system and its accuracy in the experimental barn is described in more detail in Pastell et al. (2018).

We checked placement of the collars and the positioning tags weekly. In the correct placement, tags were on the top of the cow's neck and a counterweight of 540 g kept the collar in place. If the collar had moved so that the tag was shifted 5 cm or more to the side of the neck, placement of the tag and the counterweight was corrected. Displacement of the collars was frequent, and these corrections of the placement were done in total 155 times during the experiment. If accidentally, the tags were detached, they were re-attached to the correct cow within the same day. This occurred in total 15 times during the experiment.

Additionally, feeding behaviour of the cows was measured with RIC-feeders. This system measures individual cow's roughage intake, feeding time and the number of visits to the feeder.

Two trained observers scored cow locomotion fortnightly (authors L. F. and H.L.), 16 times in total throughout the experiment. Individual cows were scored on average 5.3 times, ranging from 1 to 12 times depending on the duration the cow was engaged in the experiment. Observers collected the cows into the waiting area of the milking parlour, after which the cows were guided back to their home compartment one at a time for the locomotion scoring. Locomotion was observed from the back and the side of the cow. After scoring, observed cows were moved to a separation pen so that they would not interfere with the other observations. Observers scored the locomotion focusing on nine frequently used lameness indicators (Van Nuffel et al., 2009): 1) non-flexible joint movement, 2) tender placement of the hooves, 3) arching of the back, 4) reduced speed, 5) irregularity in the timing of the hoof placement, 6) irregularity in the location of the hoof placement, 7) reduced step overlap/tracking up, 8) increased abduction and 9) head movement. Indicator could be non-present (0) or present (1). Observers scored the locomotion independently, but their scores were merged; if differences between the observers occurred, the indicator was considered as present even if only one observer had detected it. This discrepancy between observers occurred in 246 cases out of 3384 individual indicator points. The total number of the present lameness indicators (min 0, max 9) was used as a locomotion score.

2.3. Data processing

To eliminate unwanted noise in positioning data and to improve data quality we filtered the positioning data using a heuristic jump filter (Pastell et al., 2018), which removes data points with unrealistically large change in distance, combined with a 5th order median filter. There were also 30–70 % missing data per cow per day which was interpolated using linear interpolation. Our previous work with the same setup has shown that missing data mostly occurs in the lying stalls when the cows are stationary, and that after filtering and interpolation the system reaches median accuracies of 100 % and 86 % in locating the cows in the correct stall and feeding trough, respectively (Pastell et al., 2018). For the time of milking, the cow position was interpolated to the last known location before the milking, and thus, the proportion of missing data comprised also the time spent in the milking parlour. After filtering and interpolation, days from individual cows which still had less than 5000 samples were removed from the positioning data. Due to technical issues, there were also days when the positioning system was not functioning and naturally these days were not used in the analysis; out of 214 study days we got 157 days of position data. Additionally, the days of locomotion scoring (n = 16) or hoof trimming (n = 12) were discarded from the positioning data of all cows, and from individual cows when a cow was out of its home compartment (e.g. in treatment pen for insemination; n = 38) and when the positioning tag was detached (n = 5).

Several descriptive variables about cow behavior for each day were calculated from the positioning data. The time that cows spent in the different functional areas of the barn, including the lying stalls and the feeding alley comprising the RIC-feeders, was calculated from the filtered data based on the number of points located inside the area boundary (Fig. 1). The time spent specifically in RIC-feeders was calculated from the position data with a hidden Markov model described in more detail in Pastell and Frondelius (2018). On the other hand, time spent solely in the feeding alley without feeding was calculated as a difference between positioning-based total feeding alley time and the feeding time measured with RIC-system considered as a true feeding time (Melzer et al., 2021). The daily walking distance for each cow was calculated as a sum of Euclidean distance between consecutive location points.

The daily home ranges of the cows were calculated from the positioning data. Home range is defined as the area that animal traverses during its normal activities (Burt, 1943), and it can be estimated using different statistical methods. We calculated the home range at 50 % and 95 % level, where e.g. the 50 % home range corresponds to an area where the probability to locate the animal is 0.5. We used kernel estimation of the utilisation distribution with the cell size of 1 m by 1 m, which gives the bivariate probability density to locate the cow at a given place. The home range was calculated from the utility distribution as the minimum area on which the probability to locate the animal is equal to specified value (Calenge, 2019). The analysis was implemented using R and C+ + and the adehabitatHR package (Calenge, 2006 and 2019) was used for calculating the home range.

We used lactation stage, parity, and locomotion score as categorical variables. Lactation stage was categorised into three classes, 0–30, 31–150 and > 150 days in milk, based on the earlier research showing diverging behaviour during the first month of lactation compared to middle and late lactation (Maselyne et al., 2017). Parity was also categorised into three classes as the number of cows with parity higher than 3 was markedly lower than number of cows with parity 1–2; used classes were 1) primiparous cows, 2) second lactation cows and 3) cows with parity ≥ 3. With locomotion score there were only few observations having seven or more lameness indicators present, and these observations were pooled into score ≥ 6 lameness indicators present. Other

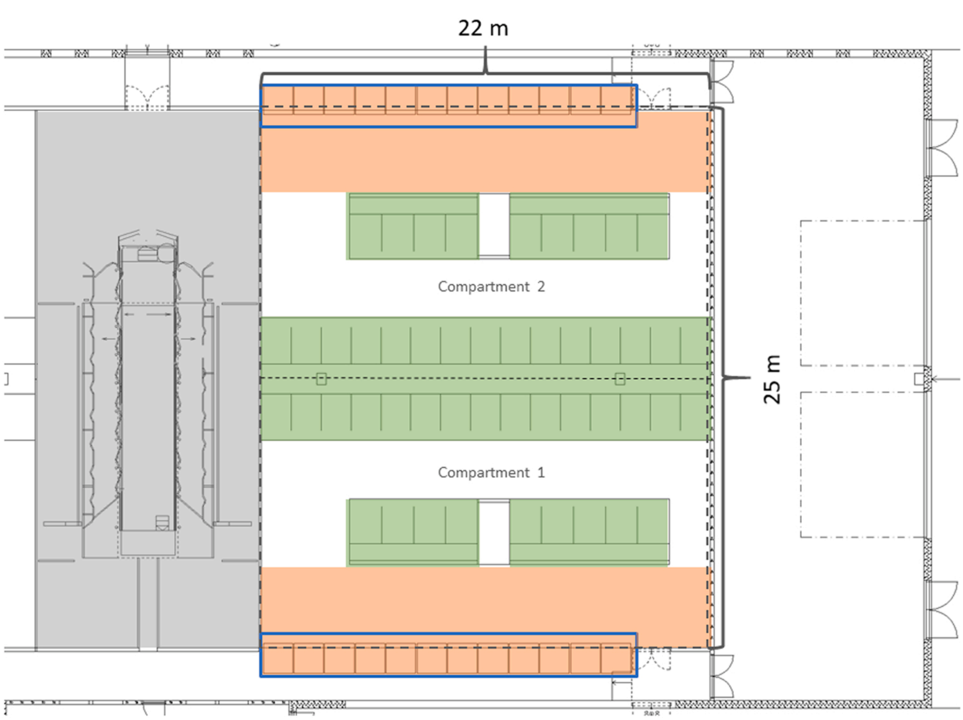

Fig. 1. Indoor positioning covered 22 × 25 m area (dashed line). Functional areas of interest were 1) lying stalls (green area), 2) feeding alley including RIC-feeders (orange area), 3) RIC-feeders (encircled with a solid blue line) and 4) feeding alley excluding RIC-feeders (orange area outside the solid blue line). Rest of the alleys within study area (white area) were not of interest in this study. Milking parlour, waiting area and separation pens (grey area) were situated adjacent to the study area and they were excluded from the positioning system.

scores, 0–5 lameness indicators present, were used as such leading to total of seven classes in the locomotion score.

Finally, behavioural variables and cow factors (parity, breed, DIM) were merged with fortnightly assessed locomotion score. We utilised the average of five consecutive days before locomotion scoring for positioning-based variables 1) daily time spent in the lying stalls (stall time), 2) daily time spent in the feeding alleys (without feeding; alley time), 3) daily time spent in the roughage feeders (feeding time) and 4) daily time spent in the feeding alley and the feeders together (total alley time), 5) daily walking distance in meter (walking distance), 6) daily home range with 50 % isopleth (home range 50 %), and 7) daily home range with 95 % isopleth (home range 95 %) of the animals. Additionally, daily feeding time measured with RIC-system (RIC feeding time) was included in the data. Because of the large amount of missing and discarded positioning data, five consecutive days of behavioural data were not always available, in which case we were forced to use fewer days. In practice, data was averaged based on two ($n = 1$), three ($n = 36$), four ($n = 60$) or five days ($n = 279$). Single days of behavioural data were not used. This led to in total 376 data points in the final dataset. The average proportion of missing data was also included in the data. Natural logarithm of this variable was used as it showed a non-linear relationship to behavioural variables.

2.4. Statistics

We fitted linear mixed models to test the associations between positioning-based daily behavioral variables and predictor variables. Models were fitted for following continuous outcome variables leading to eight individual models: stall time, alley time, feeding time, RIC feeding time, total alley time, walking distance and the home range 50 % and home range 95 %. Fixed effects in these models were class variables locomotion score, DIM, parity, and breed, and the continuous variable proportion of missing data. Correlations between fixed effects were tested with Spearman's rank correlation coefficient to check possible multicollinearity, but none of the correlations exceeded 0.5 in absolute value, and all the variables were included in the preliminary models. Using a backwards stepwise elimination, we excluded statistically not significant independent variables from the models leading to individual final linear mixed models for each outcome variable. Degrees of freedom for fixed effects were estimated using Kenward-Roger 2 option. Cow was considered as a random effect. Scatterplots and histograms of model residuals were used to check assumptions about normal distribution and homoscedasticity. If the model residuals did not distribute normally, we transformed the outcome variable by taking a natural logarithm. Outcome variables requiring transformation were alley time, total alley time and walking distance. One outlier observation was removed from alley time as it was close to zero and considered biologically implausible. The least squares (LS) means and their 95 % confidence limits were calculated for all class variables and transformed back to the original scale when necessary. Tukey's adjustment was used in pairwise comparisons. Additionally to the linear mixed models, associations between all the behavioural outcome variables were examined using Pearson correlation coefficient.

We set the statistical significance at $P < 0.05$. All the statistical analyses were performed using SAS for Windows version 9.4 with the SAS Enterprise Guide version 7.1 (SAS Institute Inc., Cary, NC, USA).

3. Results

In total, 376 locomotion scores were included in the data with the mean±SD number of lameness indicators present in the cow locomotion being 2.5 ± 1.6. More detailed numbers of different locomotion scores are presented in Table 1. Descriptive statistics for spatial behaviour of the experimental cows are presented in Table 2. Most of the behavioural variables correlated on some level with each other (Supplementary material 1). Strong correlations were evident between stall time and feeding time ($r = -0.65$, $P < 0.0001$), alley time ($r = -0.77$, $P < 0.0001$) and total alley time ($r = -0.91$, $P < 0.0001$). Positioning-based feeding time correlated with RIC feeding time ($r = 0.67$, $P < 0.0001$) and total alley time ($r = 0.73$, $P < 0.0001$), and alley time correlated with total alley time ($r = 0.88$, $p < 0.0001$).

Table 1
Number and proportion (%) of locomotion scores from all assessments included in the data (N = 376) according to the number of lameness indicators present (0–5, ≥6). Also, number of cows by parity allocated with a different number of present lameness indicators in the course of the experiment is presented. Individual cows were scored on average 5.3 ± 2.8 times.

Number of present lameness indicators	Number of scores	Proportion (%) of scores	Number of cows by parity		
			1	2	≥3
0	23	6.12	8	2	1
1	93	24.73	22	13	7
2	89	23.67	20	14	8
3	75	19.95	13	16	9
4	54	14.36	11	8	13
5	17	4.52	2	3	9
≥6	25	6.65	5	4	13

Table 2
Mean ± standard deviation, minimum and maximum values (N = 376) of daily spatial behaviour of 71 experimental cows measured with indoor positioning system or Roughage Intake Control (RIC) -system.

	Mean±SD	Minimum	Maximum
Positioning			
Stall time (h)	14.54 ± 2.30	5.55	20.43
Feeding time (h)	4.39 ± 1.14	1.36	10.13
Alley time (h)	2.67 ± 1.62	0.26	12.32
Total alley time (h)	6.58 ± 1.80	2.22	16.13
Walking distance (m)	3853.22 ± 907.88	1882.00	6770.00
Home range 50 % (m^2)	20.80 ± 5.95	8.63	43.4
Home range 95 % (m^2)	143.23 ± 23.55	83.10	208.28
RIC-system			
RIC feeding time (h)	3.91 ± 0.84	1.76	6.35

The associations between the time spent in different functional areas of the barn and the independent variables in the linear mixed models are summarised in Table 3. None of these variables were affected by missing values in the positioning data. Locomotion score was associated with the stall time ($P = 0.0037$), alley time ($P < 0.0001$) and total alley time ($P < 0.0001$); time spent in the stalls increased with increasing locomotion score (Fig. 2a) and vice versa time spent in the alleys decreased (Fig. 2c–d). In pairwise comparisons, cows with locomotion score ≥ 6 spent significantly more time in the stalls compared to cows with scores 0–3 (adjusted $P < 0.05$). Similarly, cows with locomotion score ≥ 6 differed significantly from cows with score 0–4 in alley time and total alley time (adjusted $P < 0.01$ in both), but in these variables also score 5 cows had significantly lower time spent in the alleys compared to score 0 cows (alley time, adjusted $P = 0.028$) or to score 0–2 cows (total alley time, adjusted $P < 0.05$). Parity also increased the time spent in the stalls ($P = 0.0108$) and decreased the time spent in the alleys ($P = 0.0174$ for alley time, and $P = 0.0156$ for total alley time). DIM only increased the time spent in the stalls ($P = 0.045$).

Time spent in the feeders based on the positioning data did not have a significant association with the locomotion score (Table 3). However, association with time spent in the feeders was evident in the feeding time measured with RIC-system ($P = 0.0167$); RIC feeding time decreased with increasing locomotion score (Fig. 2b). On the other hand, parity had significant effect on positioning-based feeding time ($P = 0.011$), which was not evident in RIC feeding time. In pairwise comparisons, first parity cows had significantly higher positioning-based feeding time compared to parity ≥ 3 cows (adjusted $P < 0.01$), but there was a numerical not significant difference also to second parity

Table 3
Linear mixed models describing the fixed effects associated with daily time spent in different functional areas of the barn with linear regression coefficient (β), standard error (SE) and P-value. Data comprised 376 observations and 71 cows.

Fixed effects	Indoor positioning system												Roughage Intake Control -system		
	Stall time (h)			Feeding time (h)			Alley time (log h)[ab]			Total alley time (log h)[a]			Feeding time (h)		
	β	SE	P-value	β	SE	P-value	β	SE	P-value	β	SE	P-value	β	SE	P-value
Intercept	12.41	0.60		4.05	0.27		1.379	0.12		2.09	0.06		4.12	0.16	
Locomotion score			0.0037			NS			<0.0001			<0.0001			0.0167
0	Ref						Ref			Ref			Ref		
1	0.44	0.31					-0.10	0.08		-0.06	0.03		-0.19	0.15	
2	0.54	0.33					-0.10	0.08		-0.07	0.04		-0.29	0.16	
3	0.57	0.35					-0.19	0.09		-0.08	0.04		-0.20	0.17	
4	1.01	0.36					-0.19	0.09		-0.12	0.04		-0.46	0.17	
5	1.02	0.45					-0.36	0.11		-0.19	0.05		-0.49	0.21	
≥6	1.67	0.43					-0.50	0.11		-0.25	0.05		-0.61	0.20	
Days in milk			0.045						NS			NS			NS
≤30	Ref			Ref		0.0004									
31–150	0.06	0.37		0.65	0.19										
≥151	0.50	0.41		0.45	0.21										
Parity			0.0108			0.011			0.0174			0.0156			NS
1	Ref			Ref			Ref			Ref					
2	1.14	0.50		-0.31	0.27		-0.31	0.12		-0.14	0.06				
≥3	1.48	0.52		-0.88	0.29		-0.29	0.13		-0.15	0.06				
Breed			0.0227			NS			0.0005			0.0044			NS
Nordic red	Ref						Ref			Ref					
Holstein-Friesian	1.03	0.44					-0.39	0.11		-0.15	0.05				
Proportion of missing positioning data[a]			NS			NS			NS			NS			NS

[a]Model fitted with variable transformed by taking a natural logarithm.
[b]One outlier observation was removed from the model as the time spent in the alleys was close to zero and considered biologically implausible.

cows. Based on a visual inspection, there was a larger discrepancy between positioning data and RIC-based feeding time within first parity cows compared to other parities (Supplementary material 2). This was evident also in correlations between these two variables: for primiparous cows $r = 0.55$ ($p > 0.0001$), for second parity cows $r = 0.83$ ($p < 0.0001$) and for parity ≥ 3 cows $r = 0.66$ ($p < 0.0001$).

The associations between distance-based variables and the independent variables in the linear mixed models are summarised in Table 4. Proportion of missing positioning data significantly decreased daily walking distance ($P < 0.0001$) and home range 95 % ($P = 0.0059$). None of the other independent variables affected the home range 95 %. Locomotion score influenced both daily walking distance ($P = 0.0447$) and home range 50 % ($P = 0.005$); both decreased with increasing locomotion score (Fig. 2e–f). In pairwise comparisons, it could be seen that in walking distance only locomotion score 5 differed significantly from the score 0 (adjusted $P = 0.294$). In home range, the change was not systematic and home range first numerically increases in locomotion score 1 and then began decreasing with score ≥ 6 having significantly smaller home range compared to scores 1–2 (adjusted $P < 0.05$). Additionally, primiparous cows had longer daily walking distance compared to older cows ($P < 0.0089$), and in pairwise comparisons this was evident in significant difference between first and second parity cows (adjusted $P = 0.0116$) and in tendency between first and ≥ 3 parity cows (adjusted $P = 0.0646$). Based on the scatterplot, assumption on homoscedasticity was compromised in the model with home range 50 % as a dependent variable.

4. Discussion

In this study, we showed that increasing number of lameness indicators present in cow locomotion affected the spatial behaviour of the cows measured with indoor positioning system. Instead of using a strict classification of cows to be lame or non-lame, we used several frequently used lameness indicators to evaluate the worsening lameness status of the cows. There was a numerically consistent change in spatial behaviour with the increasing number of lameness indicators present in cow locomotion suggesting that the used scoring method was able to distinguish cows with different states of lameness.

Average times spent in different functional areas of the barn followed closely the time budget of dairy cows reported in the literature: in our data, the time spent in the stalls was on average 14.5 h which corresponds to 14.6 h of summed lying and standing times in the stalls reported by Gomez and Cook (2010). Similarly positioning based feeding time and alley time were similar to their values based on continuous video observations (4.4 h vs. 4.3 and 2.7 h vs. 2.5, respectively; Gomez and Cook, 2010).

The time spent in the lying stalls increased with increasing locomotion score, and especially severely lame cows spent on average 1.67 h more in the lying stalls compared to sound cows. Vázquez Diosdado et al. (2018) reported similar results when assessing changes in space-use patterns related to lameness, although they reported higher variance in non-lame cows, and thus, treated their results with caution.

Position data gives only an indirect measure of behaviour, and it was not possible to differentiate whether cows were standing or lying in the stalls. However, based on the literature it can be assumed that cows spent most of the time in the stalls lying down (Gomez and Cook, 2010). Our results are in concordance with a study measuring lying time with accelerometers in this same barn setup with the same locomotion scoring method (Frondelius et al., 2022). In that study, lying time increased with increasing number of lameness indicators present in cow locomotion. There is plenty of research investigating the association between lying time and lameness, and the results are contradictory; several studies show increased lying time in lame cows (e.g., Thorup et al., 2015; Westin et al., 2016b; Hut et al., 2021), but some studies also report no difference between lame and non-lame cows (Yunta et al., 2012; Blackie and MacLaurin, 2019). This could partly be explained by the fact that lying time is also affected by other factors than lameness, such as lactation stage. Our results showed that cows in early lactation spent less time in stalls which is in concordance with decreased lying time in other studies (Maselyne et al., 2017; Hut et al., 2022).

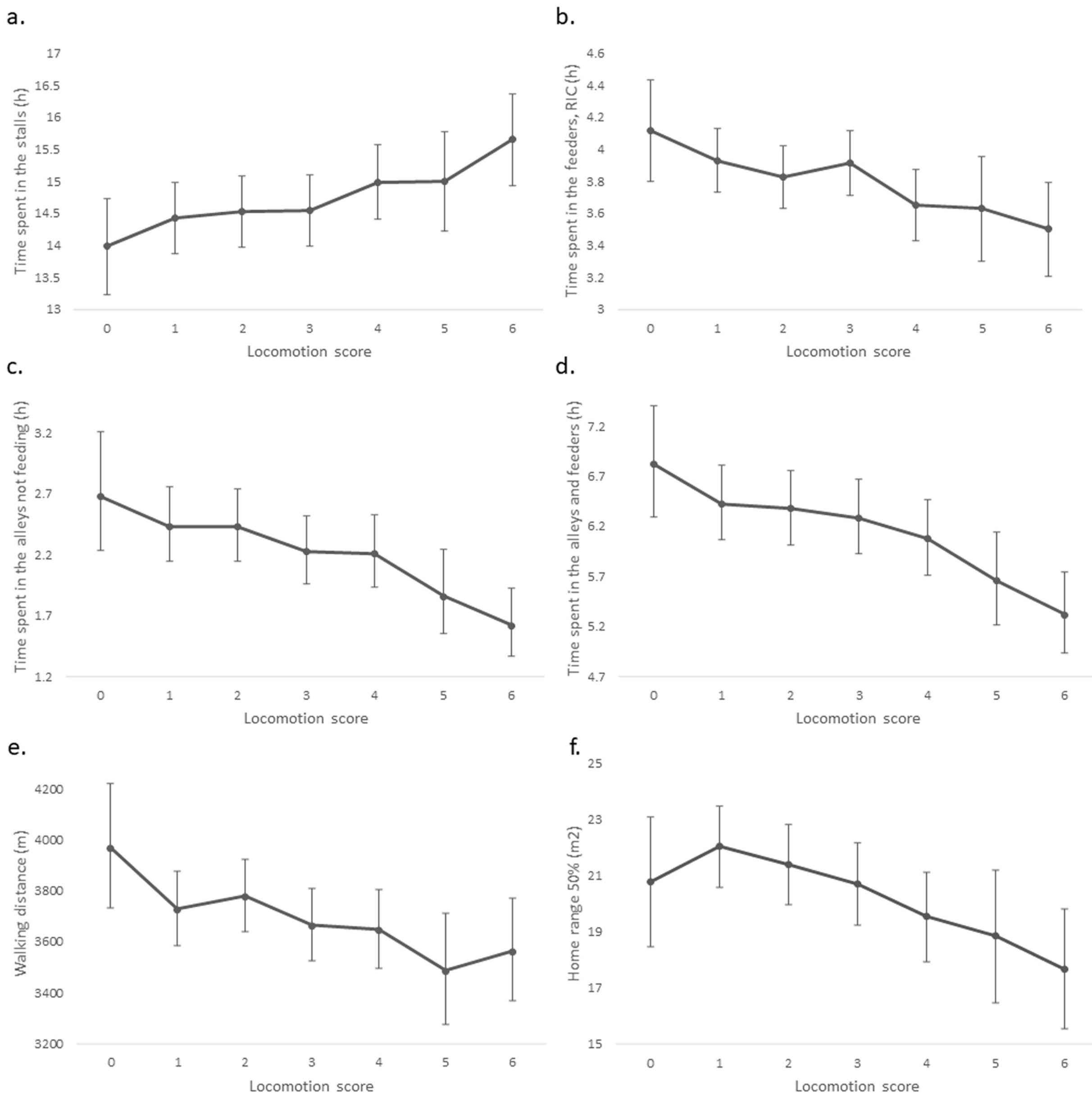

Fig. 2. Least squares means and their 95 % confidence limits for daily a) stall time (h), b) RIC feeding time (h), c) alley time (h), d) total alley time (h), e) walking distance (m) and f) home range 50 % (m^2) by the number of lameness indicators present in cow locomotion for 376 observations and 71 cows.

Conversely to stall time, cows with a higher locomotion score had a shorter feeding time based on RIC compared to sound animals. They also spent less time in the feeding alley based on the positioning data, both with and without feeding included. Also, other studies have reported reduced feeding time and number of visits to the feeder in lame dairy cows (González et al., 2008; Miguel-Pacheco et al., 2014; Thorup et al., 2016). This was evident also when the alley next to the feed bunk was included in the observed feeding area (Vázquez Diosdado et al., 2018). As many claw disorders are painful (Whay et al., 1997), this may lead to lame cows minimising their time spent standing. Yunta et al. (2012) indeed reported that lame cows stand up later and lie down earlier than non-lame cows around the fresh feed delivery, and thus, spend less time in the feed bunk.

Interestingly, the association between feeding time and lameness was not statistically evident when modeling the feeding time from the positioning data. Pastell and Frondelius (2018) reported in the same barn environment a sensitivity of 95.3 % and a specificity of 97.9 % for the hidden Markov model used in the current study. However, we found only a moderate positive correlation between position- and RIC-based feeding times. More detailed inspection showed that this correlation varied between different parities; first parity cows had the lowest correlation between feeding time and RIC feeding time, and additionally, first parity cows had a statistically higher daily feeding time which was not evident in RIC feeding time. Thus, it seems that parity was a confounding factor in the positioning-based feeding time and based on a visual inspection it is highly possible that especially in case of primiparous cows the model falsely classified animals feeding when they were actually in the alley. It is shown that misclassifications are more typical in the borders of the functional areas (Chapa et al., 2021). The measurement noise in the current positioning setup varied in the study area and was greater in the edges of the feeding alley (Pastell et al., 2018) which has likely also influenced the calculation of the feeding time.

Cows are hierarchical animals, which causes competition over feed especially in situations with limited feeding space (Grant and Albright, 2001), such as in the present study, when only 12 roughage feeders per 24 cows were available in the study compartments. Competition may

Table 4
Linear mixed models describing the fixed effects associated with distance-based variables with linear regression coefficient (β), standard error (SE) and P-value. Data comprised 376 observations and 71 cows.

Fixed effects	Walking distance (log m)[a]			Home range 50 % (m^2)		
	β	SE	P-value	β	SE	P-value
Intercept	7.90	0.04		20.76	1.17	
Locomotion score			0.0447			0.005
0	Ref			Ref		
1	-0.06	0.03		1.25	1.08	
2	-0.05	0.03		0.61	1.15	
3	-0.08	0.03		-0.07	1.21	
4	-0.08	0.03		-1.25	1.27	
5	-0.13	0.04		-1.94	1.55	
≥6	-0.11	0.04		-3.11	1.48	
Days in milk			NS			NS
≤30						
31–150						
≥151						
Parity			0.0089			NS
1	Ref					
2	-0.11	0.04				
≥3	-0.09	0.04				
Breed			NS			NS
Nordic red						
Holstein-Friesian						
Proportion of missing positioning data[a]	-0.78	0.038	<0.0001			NS

[a]Model fitted with variable transformed by taking a natural logarithm

lead to higher ranking, in this case older, cows displacing lower ranking cows, and thus, feeding more and making lower ranking cows move more frequently from one feeder to another (Foris et al., 2019). This could lead to primiparous cows loitering close to RIC-feeders and the model misclassifying them as feeding.

Besides affecting the time spent in different areas of the barn, lameness also affected distance-based behavioural variables. There was a systematic numerical decrease in home range 50 % with increasing lameness score from score 1 onward. However, only score ≥ 6 differed statistically from low scores. This range with 50 % isopleth level is considered as a core home range of the animal (Vázquez Diosdado et al., 2018). Vázquez Diosdado et al. (2018) used the same home range parameters in their study but did not find association between core range size and lameness. On the other hand, they reported a negative effect of lameness on the 95 % home range, referred as a full range. This was not evident in our data. Similarly to 50 % home range, daily walking distance had a relatively systematic numerical decrease with increasing locomotion score, with score 5 cows having statistically lower daily walking distance compared to sound animals. In literature, walking distance is a seldom referred variable in lameness research. In the study of Vázquez Diosdado et al. (2018), lameness did not affect hourly walking distance of the dairy cows. When referring to research using acceleration-based walking time and speed, results are varying; Walker et al. (2008) and Thorup et al. (2015) reported reduced daily walking time for lame cows and Beer et al. (2016) reduced walking speed, but there are also results indicating no difference between lame and non-lame cows in walking time (Beer et al., 2016) or in walking speed (Chapinal et al., 2009). However, it can be speculated that lame animals are reluctant to walk. This can also be seen in studies reporting increased return time from milking (Juarez et al., 2003) and less frequent visits to the milking robot (Miguel-Pacheco et al., 2014).

Based on our data, it seems that distance-based variables could distinguish only severely lame animals, and results were contradictory to another study (Vázquez Diosdado et al., 2018) using the same or similar variables. Most likely reasons to this were barn layout and management; in our setup, cows were housed in groups of 24 animals in a small area (Fig. 1). The feeding area was situated close to the lying area, and even lame animals had easy access to all stalls and RIC-feeders. This was not the case in the study of Vázquez Diosdado et al. (2018) with an animal group of 120 cows in a large area with long distances, and where lame cows showed higher side fidelity in lying area.

Additionally, in our study, proportion of missing positioning data had a significant effect both on daily walking distance and home range 95 %. It seems that distance-based variables are sensitive to data quality unlike the time spent in different functional areas of the barn. The UWB setup used in this study was not designed for the use in barn environment, which is a challenging environment for indoor positioning with obstacles and signal reflecting surfaces (Gygax et al., 2007; Hindermann et al., 2020). Ultra-wide band systems commercially available for barn use have shown better performance in several studies (e.g. Ren et al., 2021b, Meunier et al., 2018), but all the studies do not report the performance of the UWB system and proportion of the missing data (e.g. Veissier et al., 2017, Wagner et al., 2021). Reporting of the system performance is of importance for estimating the validity of results as most of the indoor positioning systems appear to have missing data of some degree: e.g. 19 % in the setup of Vázquez Diosdado et al. (2018) and 4–18 % in the setups of Ren et al. (2021b). Additionally, proportion of missing data can vary largely between different tags (Ren et al., 2021b). On the other hand, quality of the calibration of the positioning setup can markedly affect the quality of positioning data (Melzer et al., 2021). However, our results show that associations between lameness and time spent in different functional areas of the barn are evident even with a high proportion of missing positioning data.

Overall, the method used to merge daily behavioural data and locomotion score can affect the results. Behaviour data is usually collected over a long period of time, while locomotion score is an instantaneous time point. We decided to use the average daily behaviour from the five consecutive days before the locomotion scoring. Averaging the daily behaviour over a certain number of days before assessment of locomotion is used also in several other studies (e.g. Solano et al., 2016, Blackie and MacLaurin, 2019). However, this approach can potentially normalise the lameness caused variation between the days as behaviour of cows has been shown to consistently change during the days before the diagnosis of a hoof disorder (Magrin et al., 2022). In our study, however, locomotion scoring was conducted on a regular basis fortnightly and the assessed score does not represent the diagnosis day or "peak lameness"; on the assessment day cow may be in deteriorating or in improving state. Additionally, many claw horn lesions develop gradually (Hoblet and Weiss, 2001), and sudden changes in lameness status or in cow behaviour are not expected. Five-day average was used also to minimise random variation and variation caused by the measurement system.

The prevalence of lameness in the current dataset was 25.5 % if cows having ≥ 4 lameness indicators present in their locomotion were considered to represent locomotion scores 2–3 in AHDB Dairy Mobility Score (AHDB, 2020). This is in concordance with the lameness prevalence of 23 % in Finnish loose-housing systems reported by Sarjokari et al. (2013). However, it must be noted that prevalence number presented from the current study is the prevalence from all the assessed locomotion scores rather than the prevalence of cow-level study population. Additionally, there are several limitations regarding reliability of subjective locomotion scoring (Schlageter-Tello et al., 2014). For example, environmental factors can affect cow locomotion (Van Nuffel et al., 2015a), and it is possible that scoring cows on slatted floors in our setup overestimated the prevalence of lameness.

One of the advantages of indoor positioning is that it enables measuring multiple different behaviours with a single system. For example, Grimm et al. (2019) reported a strong interaction between daily lying and feeding time in regard to lameness, and taking this interaction into account would most likely improve the development of predictive models in automatic lameness detection. However, location of the animal can give us only an indirect measure of what the animal is actually doing. Combining multiple sensors could aid classifying cow behaviour more accurately, especially in case of behaviours that show low classification success with a single sensor like walking. Combining positioning and accelerometers has shown promising results in measuring feeding behaviour (Barker et al., 2018), lying time, standing time, transitions between these two, and walking (Wang et al., 2018). Heading towards possible automatic lameness detection systems it would be worthwhile to conduct this kind of comparative study with different sensors measuring cow behaviour simultaneously with positioning. Additionally, cow behaviour is affected also by many other factors than lameness or other health problems of interest. For example, farm effect on the behaviour of the cows is normally strong (e.g. lying behaviour, Ito et al., 2014; feeding behaviour, von Keyserlingk and Weary, 2010), which was evident also in our results compared to study of Vázquez Diosdado et al. (2018), and thus performance of predictive models based on the data collected from a single farm is often poor on the other farms (e.g. ketosis, Steensels et al., 2017). Thus, it is advisable to collect data from multiple farms and over a long time period or over several lactations to account for as much between-farm and within-cow variation as possible for training the predictive model for automatic lameness detection (Riaboff et al., 2022).

5. Conclusions

Spatial behaviour of dairy cows differed between cows with different locomotion scores. This was evident especially in time spent in different functional areas of the barn. Our results show that indoor positioning of dairy cows has a potential to contribute to development of automatic lameness detection. However, reliability of the current system should be improved with minimising the amount of missing data as this would improve the calculation of distance-based variables such as walking distance.

CRediT authorship contribution statement

Each author declares substantial contributions through the following: **Lilli Frondelius, Stephanie Van Weyenberg, Heli Lindeberg, Matti Pastell:** the conception and design of the study, or acquisition of data, or analysis and interpretation of data. **Lilli Frondelius, Stephanie Van Weyenberg, Heli Lindeberg, Annelies Van Nuffel, Jarissa Maselyne, Matti Pastell:** drafting the article or revising it critically for important intellectual content. All co-authors have read and approved the version of the manuscript that is submitted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2022.105763.

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