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Sensor-based activity patterns of healthy calves housed in large groups

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ABSTRACT

Young calves are susceptible to disease. Studies indicate that calf activity often changes prior to a clinical diagnosis. Accelerometers can monitor activity continuously, offering an opportunity for early detection of disease in individual reared calves, based on deviation from their 'normal' activity patterns. This requires the prior understanding of these 'normal' activity patterns in healthy calves. This study aimed at describing the group activity patterns of healthy group-housed calves. Holstein and crossbred calves (n = 231; 17 ± 4 d of age at arrival) were housed in six large pens (N = 38 ± 2 calves per pen). Calves had milk replacer via automated milk feeders twice or three times daily and *ad libitum* access to solid feed. High frequency activity data were continuously recorded from 6 to 28 weeks of age using leg accelerometers. Clinical examination was performed twice per week between 8 and 25 weeks of age, whereby any symptom of disease was scored based on the severity, and summed to reach a total 'health score'. Activity data from sick calf days between two healthy days were extrapolated to surrounding 'none-health monitoring' days between the corresponding two healthy days. Generalized additive models with a Gaussian response were used to estimate daily group patterns of 'being active' and 'being inactive' per week, corrected for trends over time/age. Four features were extracted from the data and used in the model based on weekly averages: number of peaks, time (of the day) at which peaks occurred, the height (i.e. absolute value) of each peak, and the proportion of the night activity. The results showed that normal activity patterns can be described using the above features. The number of peaks in activity in a day went from 4 to 3 over the fattening period, with most peaks corresponding to availability times of new milk replacer. A peak in activity was consistently observed prior to darkness. Night-time activity was consistently around 20 % between 8 and 20 weeks of age and gradually increased to 27 % between 21 and 25 weeks of age. A leave-one-out analysis showed a medium accuracy (0.646) of using the fitted model to predict activity patterns of individual calves, indicating that most calves deviate in some way from this average pattern. The next steps are to identify which factors (e.g. personality, weight) lead to individual differences between calves in terms of activity and to develop valid models to detect deviations indicative of health issues in calves.

1. Introduction

Calves raised intensively for milk or meat, i.e. dairy or veal, are prone to disease, with mortality rates of up to 5 % being reported (Ganaba et al., 1995; Donovan et al., 1998; Svensson et al., 2003; Snowder et al., 2006; Brscic et al., 2012; Pardon et al., 2012a, 2013). In the first weeks of life, diarrhoea is often the main problem, whereas later on in life respiratory disorders, such as pneumonia, become more prevalent (Svensson et al., 2003, 2006). Besides the impact on welfare, diseases in calves cause significant economic losses, through treatment, impaired growth or mortality (Ganaba et al., 1995; Snowder et al., 2006).

Moreover, antimicrobial resistance linked to high antibiotic use is a major societal concern, and efforts in the past two decades have been made in Europe, for example in the Netherlands, to reduce antibiotic use in farm animals (SDa, 2021). Despite antibiotic use being decreased by half in the livestock sector, the veal sector is still a relative heavy user compared to other sectors (Catry et al., 2007; Cook et al., 2011; Graveland et al., 2011; Pardon et al., 2012b, 2013; Yang et al., 2020). The

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veal sector in the Netherlands has the highest treatment prevalence at group level (over 97 % of total use), probably due to the ease of oral administration through the milk replacer (Pardon et al., 2012a, 2012b) and the lack of early warning systems indicating calf diseases leading to fast spreading of infectious diseases.

In the Netherlands, veal calves are typically transported from the dairy farm to the veal farm (via an assembly centre) between 14 and 35 days of age. Veal calves stay at the fattening farm until they reach their slaughter weight, which for white veal calves is typically around 225 kg at 25 weeks of age (Berkhout et al., 2021). Risk factors for morbidity, mortality and antibiotic use in calves have been frequently investigated in the past, and include: failure of transfer of passive immunity from colostrum (Stull, Mcdonough, 1994; Torsein et al., 2011; Windeyer et al., 2014), low birth weight (Wittum et al., 1994), low body size at arrival on the veal farm (Brscic et al., 2012), solid feed provision (Snowder et al., 2006; Brscic et al., 2011), mixing calves from different farms (Autio et al., 2007; Pardon et al., 2012a), an abnormal navel, dehydration, presence of a sunken flank, arriving in the summer (Renaud et al., 2018) and winter (Bokma et al., 2019), higher numbers of calves transported to the same farm (Sandelin et al., 2022), larger age variation in the same arrival batch (Sandelin et al., 2022), beef breed (higher use compared to dairy and crossbreeds; Bokma et al., 2019), calves transported at an early age (Marcato et al., 2022).

Additional findings indicate that clinical signs of bovine respiratory disease are visible only 12–136 hours after the onset of fever (Timsit et al., 2011a), that 74 % of fever episodes can go undetected and untreated, for example, in beef bulls in fattening operations (Timsit et al., 2011b), and that there is a low predictability of lung lesions at slaughter from clinical signs *in vivo* in veal calves (Leruste et al., 2012). Although only 6.8 % of veal calves were observed with clinical signs of respiratory disorders during visits to 174 veal farms in Europe, half of the lungs showed some level of damage at slaughter (Leruste et al., 2012). In terms of gastrointestinal disorders, such as diarrhoea and ruminal drinking, aetiologies are often multifactorial and complex (Klein-Jöbstl et al., 2014). It is, moreover, difficult to distinguish diarrheic from non-diarrheic calves in groups (Svensson et al., 2003), and it is, therefore, difficult to promptly treat calves at the individual level. Other predisposing factors are related to the ability of farmers to accurately control the health status of individual calves: a less-experienced farmer, fewer veterinarian visits, and a higher number of calves per pen (Svensson et al., 2003; Brscic et al., 2012).

Taken together, these studies above clearly demonstrate the need for improved methods to detect health problems. However, the contrast between the high density of the animals in the current conventional Dutch veal production system, and lack of personnel (or money or resources) farm staff are facing, made it challenging to add extra workload to the current daily practices of farm staff. To be able to identify a sick calf at an earlier stage, precision livestock farming (PLF) tools might provide support to the conventional health check by farm staff. PLF tools have the potential to help with the identification of the ontogenesis of disease in individual calves by providing alerts to farm staff, enabling more focused health checks by these staff and possible timely, individual treatments and separation of diseased animals, reducing further spread of diseases. For example, leg, neck or eartag accelerometers monitor calf activity, and have been shown to have potential in disease detection such as bovine respiratory diseases (Ramezani Gardaloud et al., 2022) and neonatal calf diarrhoea in calves (Goharshahi et al., 2021).

Before developing algorithms aiming at identifying deviations from what could be considered normal behaviour in the given system, a prerequisite is to understand what the 'normal behaviour' looks like, and hence study the activity patterns of healthy calves. The objective of the current study was therefore to define these 'normal' patterns of activity in healthy group-housed veal calves using generalized additive models applied to accelerometer data. In particular, we answer the following questions: i) what does the daily activity pattern of healthy calves typically look like? ii) how do activity patterns of healthy calves change over the fattening period (from 8 to 25 weeks of age)?

2. Materials and methods

The experiment was approved by the Central Committee Animal Experiments (Centrale Commissie Dierproeven, CCD; beschikking 2655) in the Netherlands.

2.1. Animals and management

The study was carried out between July 2021 and January 2022 on a Dutch commercial veal farm. Two-hundred and thirty-one calves (approximately 2 weeks of age at arrival; mixed gender with most females being crosses of Holstein-Friesian x Belgian Blue and males being Holstein-Friesian or Holstein-Friesian x Belgian Blue. There were also a few other minority breeds, typically crossed meat and milk) from the same batch were included. Calves were kept individually in so-called 'baby boxes' inside the group pens for the first 4 weeks following arrival (Fig. 1, left panel), and were thereafter released into six large pens (9.15 ×7.5 m, N = 38 ± 2 calves per pen, mean ± SD, Fig. 1, right panel). The baby boxes were 110 × 80 cm and allowed calves to have tactile contact with neighbouring calves, as well as visual and auditory contact with calves in the same pen. Calves were re-grouped three times (average age of calves: 90 ± 4 d, 107 ± 4 d, 129 ± 4 d) based on body size by farm staff. Calves were kept in the same barn during the entire fattening period. The ventilation system in the barn used a combination of electronic ventilation fans. Each pen in the group housing was equipped with enrichment in the form of rubber teats for sucking and chewing (approximately 6 mounted on the wall and approximately 6 in a bucket hanging from the roof), one brush, one mineral block and one large yellow skippy ball hanging from the roof. Pens were equipped with rubber coated slatted flooring. Artificial lighting was on when farm staff were present. Group and individual medicine treatments were administrated and recorded by farm staff. Calves were given ornithine transcarbamoylase, doxycycline, tilmoved, and ampisol on arrival and after arrival following the protocol from the farm, via the milk replacer. All herd level administration were supplied in the milk replacer through the automatic milk feeders (AMF). Sick calves were treated with antibiotics and (or) anti-inflammatories. Calves were slaughtered at 27–28 weeks of age.

2.2. Feeding

During individual housing, calves were bucket-fed with 2 L of milk replacer twice per day at approximately 8:00 h and 18:00 h, and had *ad libitum* access to the solid feed. During group housing, calves from the same group had access to one AMF (Förster-Technik GmbH, Engen, Germany). A new allowance of milk replacer was available to the calves via the AMF twice daily (between week 8 and 20, at around 4:00 h and 15:30 h, each meal period lasted about 6 h) or three times daily (from week 21 onwards, at around 4:00 h, 11:30 h, and 16:30 h, each meal period lasted about 5–6 hours). The average amount of milk replacer allowance increased from 6 L to 14 L per week gradually over the entire fattening period (Table 1). Water was supplied 6 h per day in two periods (from 8:00 h to 11:00 h, from 20:00 h to 23:00 h) through an automatic water drinker. Calves had *ad libitum* access to solid feed in one shared trough per group. The solid feed onsisted of chopped straw (~15 %) and concentrate. Concentrate contents was as follows: day 1–35 - protein:12.5 %, fat: 4.5 %, crude fibre: 7.7 %; day 14–80 - protein: 17.0 %, fat: 4.0 %, crude fibre: 5.3 %; Day 70 onwards - protein: 14.0 %, fat: 4.0 %, crude fibre: 5.3 %.

2.3. Activity

Accelerometers (SmartTag, Nedap N.V., Groenlo, the Netherlands) were attached to one of the front ankles of each calf on the day before

Fig. 1. Set-up of the housing. Left, individual 'baby boxes'; Right, group housing.

Table 1
Average milk replacer intake in healthy calves (XX ± SD).

Week of age	Milk replacer intake (mL)
8	6529 ± 826
9	6580 ± 875
10	6453 ± 886
11	6762 ± 900
12	6969 ± 887
13	7241 ± 933
14	7490 ± 869
15	7570 ± 929
16	7703 ± 1036
17	7841 ± 1018
18	8058 ± 1068
19	8346 ± 1096
20	8845 ± 1215
21	9526 ± 1168
22	10283 ± 1268
23	11117 ± 1345
24	11943 ± 1449
25	12675 ± 1770

they were released into their groups, at approximately six weeks of age. Animals accepted wearing the accelerometers quickly (only a few calves tried to kick off the sensors after attaching the sensors, but got used to it after a few hours). High frequency sampling (the built-in algorithm process to aggregate data per 15 min) of lying time (i.e. in minutes), standing time (i.e. in minutes), walking time (i.e. in minutes), number of lying bouts, and step count were continuously recorded by accelerometers throughout the fattening period (6–28 weeks of age), and uploaded to the server located at the sensor company. Data was downloaded from the server.

2.4. Health score

A health protocol was created (Table 2) based on the Calf Health Scorer (McGuirk and Peek, 2014) and the Welfare Quality Protocol for veal calves (Welfare Quality®, 2009). Clinical examination was carried out twice per week and was performed by a trained staff (DS) between 8 and 25 weeks of age. Intra-observer reliability was verified by repeated scoring of calves during previous experiment in this project (100% agreement was noted). A total health score was calculated by adding the scores obtained on all the health parameters, except temperature and diarrhoea. A sick calf day was defined as meeting either one of the following criteria: i) a total health score ≥ 5, ii) a temperature score $= 1$, or iii) diarrhoea score $= 1$.

2.5. Statistical analyses

2.5.1. Data preparation

Activity data were stored and organized in excel spreadsheets (version 2016, Microsoft Corp., Redmond, WA, RRID:SCR_016137). Pre-processing and statistical analyses were performed using the R statistical software (version 4.3.0; R Core Team, 2022) and RStudio environment (version 2023.03.1; RStudio Team, 2020). Calves with missing activity data for a period longer than a day, which indicated that they had been moved to the sick pen, were removed from the dataset. Sick calf days (as defined above) between two healthy days were extrapolated to surrounding 'none-health monitoring' days between the corresponding two healthy days, to obtain a conservative dataset in terms of including only days where calves were healthy with a high level of confidence. The final activity dataset used for statistical analysis included data from 218 calves over a period of 18 consecutive weeks. To characterize the activity pattern of the group of 218 calves over time using the statistical model described below, the numerical variables "week", "day" and "minute", that respectively represent the number of weeks from the start of the study, the number of days from the start of the study and the number of minutes from the start of the day, were created. These three variables represent different scales of time and are used as explanatory variables to describe and predict the activity of the calves. The activity of calves is measured by the numerical variables "lying time", "standing time" and "walking time", that represent the rounded-off number of minutes, out of a 15-minute period, that a calf has spent lying, standing or walking. Because these three numerical variables measuring activity are related (the value of one is a linear combination of the other two), they were transformed into a single categorical variable "activity", with categories "lying", "standing" and "walking". Our original goal was to employ multinomial logistic regression to predict the categorical "activity" using the three numerical time variables. However, due to the large size of the activity dataset, fitting this complex model was computationally infeasible. Therefore, we transformed the three-category variable "activity", with categories "lying", "standing" and "walking", into a two-category, binomial variable: "inactive" and "active" by combining the original "standing" and "walking" categories. This modification allowed us to use a logistic regression model that was computationally feasible.

2.5.2. Model

The statistical model used to describe the activity pattern of the group of calves is provided in Eq. (1). This model uses the binary variable "activity" as response variable and the three numerical time variables "week", "day" and "minute", as explanatory variables. To describe the activity patterns in a flexible manner, the effects of the three time variables were modelled with cubic splines, which are non-linear smooth functions. Specifically, a smooth function f_0 was used for "day" to describe globally the activity patterns and a smooth function f_j

Table 2
Calf health score[a].

Score	0	1	2	3
Temperature (°C)[b]	37.8–39.4	> 39.4		
Navel infection	Normal	Enlarged, not warm or painful	Enlarged, with pain, heat or moisture	
Prepuce/urine sucking	Normal	Moisture, enlarged, not warm, without pain	Moisture, swollen, warm	
Attitude	Normal, bright, alert, responsive	Dull but responds to stimulation	Depressed, slow to stand or reluctant to lie down	Unresponsive to stimulation
Behind in weight and condition[c]	Normal	15–30 %	> 30 %	
Bloat	Normal	One side	Two sides	
Abnormal breathing	Normal	> 40/min		
Cough	No cough	Single cough occurrence	Repeated or occasional spontaneous coughs	Repeated spontaneous coughs
Diarrhoea (calf number)	Normal	Faecal score = 2 or 3		
Nose	Normal	Small amount of unilateral cloudy discharge	Bilateral cloudy or excessive mucus discharge	Copious bilateral mucopurulent discharge
Eye	Normal	Small amount of ocular discharge	Moderate amount of bilateral discharge	Heavy ocular discharge
Ear	Normal	Ear flick or head shake	Slight unilateral droop	Head tilt of bilateral droop
Joint, lameness, bursa problems (note down front or hind legs)	Normal	Slight swelling, not warm or painful	Swelling with pain or heat	
Skin damage	Normal	Single source of damage	Multiple sources of damages	
Faecal (at pen level)	Normal	Semi-formed, pasty	Loose, but stays on top of bedding	Watery, sifts through bedding

[a] Total score besides temperature and diarrhoea: 4 (watch), 5 or more (treat), faecal score: 2 or 3 (treat), temperature/diarrhoea= 1 (treat).
[b] Temperature: write down the actual temperature.
[c] To check calf condition, compare our experimental calves with the rest of the stable (and not just the other calves within the same pen).

for “minute” was used to describe the activity patterns within a weekly basis. The factor “pen” (α_q) was included in the model as a standard fixed effect. Denoting by $y_{ijkl} \in \{0,1\}$ the observed response (0 for “inactive” and 1 for “active”), the logistic model is:

$$\begin{cases} y_{ijkl} \sim Bern\left(m_{ijkl}, \quad p_{ijkl}\right) \\ logit\left(p_{ijkl}\right) = \log\left(\frac{p_{ijkl}}{1 - \quad p_{ijkl}}\right) = \mu + \sum_{q=1}^{6} \alpha_q + f_0(x_k) + f_j(x_l) \end{cases} \quad (1)$$

Here, $Bern(m,p)$ denotes a Bernoulli distribution with number of trials m and probability p. Furthermore, p_{ijkl} represents the probability that calf $i \in \{1,\ldots,218\}$ is active in week $j \in \{1,\ldots,18\}$, day $k \in \{1,\ldots,126\}$, and minute window $l \in \{1,\ldots,96\}$ (there are 96 15-minute windows per day), whereas α_q denotes the effect of pen $q \in \{1,\ldots,6\}$ (the contrast $\alpha_1 = 0$ was used to ensure model identifiability).

The above model is a generalized additive model (GAM) and was fitted using the function *bam* (Wood et al., 2015, 2017; Li and Wood, 2019) of the R package *mgcv* version 1.8–42 (Wood, 2011), which is designed to fit GAM models to very large datasets.

Our interest lies in the estimated smooth curves of the logistic model that describe activity patterns, but also in summary statistics of these curves such as the number, time and height of peaks, and the proportion of night activity (before 4 am and after 9 pm). These summaries were extracted from the fitted model.

2.5.3. Leave-one-out analysis

As it is not possible to obtain variance estimates for the extracted summary statistics directly, we conducted a leave-one-out analysis (LOO). This consisted in iteratively removing one calf from the dataset, refitting the logistic model using the data of all other calves, and extracting summary statistics from the estimated curves. This process was repeated for each calf in the dataset. The variances of the LOO summary statistics were used as estimates of the variance of the summary statistics on the complete activity dataset.

Although the prediction of calf activity is not the main focus of the present paper, the LOO was also used to assess the out-of-sample prediction performance of the model. Each fitted model was used to predict the activity status of the calf that was left out. A data point was classified as "active" when its estimated probability of being active was greater or equal than $t = 0.5$. Then, performance was assessed by comparing predicted and observed classifications by reporting the sensitivity, defined as the proportion of predicted active states among truly active states, and the specificity, that is defined as the proportion of predicted inactive states among truly inactive states. Instead of reporting the sensitivity and specificity based on a single value for the threshold t, the receiver operating characteristic (ROC) curves that display sensitivity as a function of 1 - specificity for a range of values for t are provided. The area under the ROC curve (AUC) is a numerical summary of this curve. ROC curves and AUC are reported for each left-out calf of the LOO and overall.

3. Results

The average percentage time being active per week is summarised in Table 3 (the full summary of the weekly average of daily activity can be found in Appendix 1). At 8 weeks of age, healthy calves spent on average 31.5 % of their time per day being active. As the calves grew older, they spent gradually more time being active (37 % at 25 weeks of age). The proportion of night activity accounted for around 20 % of the total time

Table 3
Average percentage activity in healthy calves.

Week of age	Active (%)
8	31.5
9	32.5
10	32.1
11	32.9
12	34.1
13	33.1
14	33.4
15	33.3
16	33.5
17	33.9
18	35.8
19	35.2
20	35.7
21	36.4
22	36.2
23	36.3
24	37.0
25	37.0

being active between week 8 and week 20, and increased from week 21 to reach to 27 % of the total time being active on week 25. The ROC curves of the LOO for each calf of being active are presented in Fig. 2. On average, the model had a medium accuracy (0.646) in its prediction of whether a calf was active or not at any given time, with a low sensitivity (0.355) and high specificity (0.834).

Averaged daily activity patterns per week were plotted as smooth group curves from week 8–25 (Fig. 3). Four features (i.e. number of peaks, height of each peak, time of each peak, and the proportion of night activity) were extracted from these group curves and these are shown in Table 4. Though timing of peaks varied a little, the activity of healthy group-housed calves showed four peaks from 8 weeks of age (on average at 4:48 h, 10:33 h, 16:05 h, and 21:07 h) to 20 weeks of age (at 5:31 h, 10:48 h, 16:19 h, and 21:21 h). In contrast, the activity of healthy group-housed calves showed only three peaks from 21 weeks of age (5:31 h, 11:02 h, and 21:07 h) to 25 weeks of age (5:46 h, 12:29 h, and 21:36 h). The timing of each peak shifted gradually to slightly later times as calves grew older, except the first peak at 9 weeks of age, the third peaks at 10 and 17 weeks of age, and the fourth peak at 17 weeks of age. In terms of the height of peaks, which indicates a higher probability for calves to be active at this time, there was a shift over time as to which of the peaks was the highest. Between 8 and 12 weeks of age, the fourth peak of activity was the highest compared with other weeks (based on means comparisons). At 13 weeks of age the second and fourth peaks were the highest. Between 14 and 21 weeks of age, the second peak was highest. Between 22 and 25 weeks of age, the third (and last) peak was the highest. The proportion of night activity (defined as the time between 21:00 h and 4:00 h) was relatively stable between 8 and 21 weeks of age except at 17 weeks of age where a slight drop in night activity was identified. The proportion of night activity increased between 22 and 25 weeks of age.

4. Discussion

The aim of this study was to describe the daily activity pattern of healthy, group-housed calves and changes in these activity patterns across the fattening period. The rationale behind this study was that the understanding of the behavioural patterns of healthy individuals would help identify deviations in these patterns in sick individuals, or in individuals experiencing other negative states such as social stress (Millman, 2007). In particular, large individual variation in activity patterns was found within groups of healthy calves, and activity patterns may be affected by the specific management routines implemented at the farm (e.g. in pigs; Bus et al., 2021). The calves were regrouped three times during the trial, and although the majority (above 95 %) of calves remained in the same pen throughout the fattening period, these changes are likely to have had negative welfare consequences on the groups. Studies have previously shown preferential social bonds

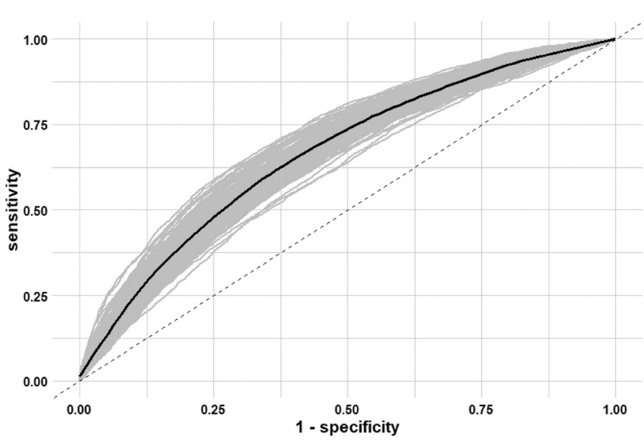

Fig. 2. ROC curves of the LOO analysis on individual activity patterns.

between calves, whereby paired-housed dairy calves show a preference for their pen-mate (Lindner et al., 2022) and experience less stress when separated from their home pen if the preferred calf is present (Færevik et al., 2006). Future research should investigate how regrouping affect activity in healthy calves. In addition, group patterns in healthy calves might provide a reliable trend of how the normal activity of calves changes across the fattening period. Group patterns on behaviour could be used as the benchmark for developing a health monitoring model for individual calves; and provides information of the management applied. By creating a daily pattern per week, we generated the temporal characteristics of daily activities, adding this to the more common analysis of absolute numbers of activities (or features).

To describe the daily group activity patterns in healthy calves, we drew smooth curves of the activity for each week of the fattening period. These smooth curves describe the activity patterns via so-called 'extracted features': the number of peaks in activity, the time at which the peaks took place, the height of the peaks, and the proportion of night activity. This is a novel approach in calves (but not in pigs: Bus et al., 2023) as previous studies typically describe activity either in minutes per day (e.g. Omontese et al., 2022), or display average calf activity (standing or lying) across the day on a graph, without extracting key features (e.g. based on direct manual observations; Webb et al., 2012, 2015). The benefit of the smooth curves is that they represent the expected fluctuations in variables for specific moments of the day when all other parameters in the model are fixed. The partial effects are adjusted or scaled variables for all other variables, e.g. pen, in the model including intercept, allowing generating the smooth curves.

We observed a relatively stable number of four peaks of activity between week 8 and week 20 on average, followed by a stable number of three peaks between week 21 and 25. Between week 8 and 20, milk replacer was made available by the AMF twice daily (at around 4:00 h and 15:30 h, each meal timeslot lasting approximately 6 h), and was increased to three times daily from week 21 onwards (at around 4:00 h, 11:30 h, and 16:30 h, each meal timeslot lasting approximately 5–6 hours). The successively increasing height of peaks showed that calves became more and more active across the day, from morning to evening, which is consistent with previous research (Alawneh et al., 2020). Over time, when calves grew older, the respective height of peaks increased, especially the first and the second peaks between week 8 and 20.

The first peak in all weeks occurred approximately one hour after the start of the first session of the milk replacer supply, with a constant timing of peaks in most of the weeks, i.e. 5:17 h (between week 8 and 20) and 5:31 h (between week 21 and 25), suggesting that the first peak is closely linked to the timing of the morning milk feeding.

Similarly, between week 8 and 20: the third peaks occurred right after the start of the afternoon milk timeslot (15:30 h), and the relative stable height of the third peaks indicated the normal activity level caused by the feeding; the difference of heights between the first and the third peaks narrowed down gradually as calves grew older, till the third peaks reached a similar heights as the first peaks at weeks 19 and 20. These initial results seem to be in line with recent studies reporting that the activity patterns of calves are related to feeding time (Omontese et al., 2022; Giannetto et al., 2023).

The number and timing of peaks in activity, however, do not match exactly the number and timing of milk feeding timeslots, as would be expected if activity would match feeding moments. In particular, an increase in milk feeding timeslots was expected to lead to a higher number of peaks of activity, but instead we noted a decrease in the total number of peaks from four to three. The decrease from four to three peaks in healthy calves in the weeks when three milk feeding timeslots were allowed, seems to point to a better ability of calves to focus their activity around feeding moments as they grow older. It is likely that a frequency of two milk feedings per day is too far from the voluntary milk feeding frequency of calves, which seems to be around 7–8 feedings per day (Webb et al., 2014), leading calves to visit the AMFs more

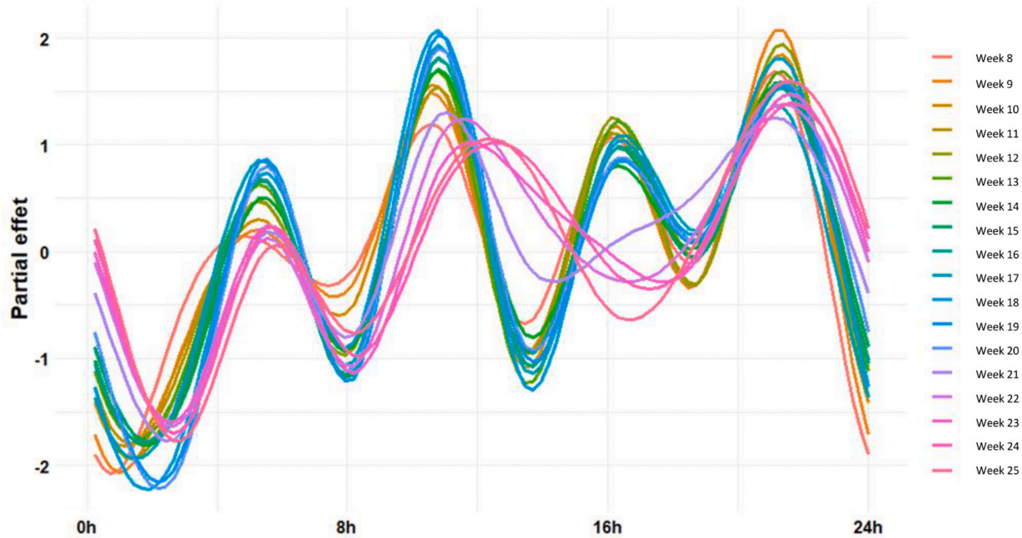

Fig. 3. Smooth curves of averaged daily group activity patterns per week plotted from week 8 to week 25 of calf age.

Table 4
Extracted features of the smooth curves of active activity patterns in healthy calves.

Week of age	Number of peaks	Proportion of night activity	Time of peak (1st)	Time of peak (2nd)	Time of peak (3rd)	Time of peak (4th)	Height of peak (1st)	Height of peak (2nd)	Height of peak (3rd)	Height of peak (4th)
8	4	0.20	4:48	10:33	16:05	21:07	0.15	1.20	1.06	1.69
9	4	0.21	5:17	10:33	16:05	21:21	0.20	1.49	1.11	2.08
10	4	0.21	5:17	10:33	16:19	21:21	0.30	1.56	1.17	1.85
11	4	0.22	5:17	10:48	16:05	21:21	0.47	1.54	1.11	1.94
12	4	0.21	5:17	10:48	16:05	21:21	0.48	1.69	1.25	1.95
13	4	0.21	5:17	10:48	16:19	21:21	0.63	1.69	1.22	1.69
14	4	0.20	5:31	10:48	16:19	21:21	0.50	1.70	0.80	1.59
15	4	0.21	5:17	10:48	16:19	21:21	0.66	1.80	0.97	1.55
16	4	0.20	5:17	10:48	16:19	21:21	0.68	1.81	0.98	1.53
17	4	0.18	5:17	10:48	16:33	21:07	0.85	1.93	1.08	1.37
18	4	0.20	5:31	10:48	16:19	21:21	0.74	2.07	1.03	1.81
19	4	0.21	5:31	10:48	16:19	21:21	0.87	2.03	0.85	1.56
20	4	0.21	5:31	10:48	16:19	21:21	0.80	1.90	0.88	1.59
21	3	0.21	5:31	11:02	21:07	NA	0.18	1.31	1.25	NA
22	3	0.24	5:31	11:31	21:21	NA	0.13	1.24	1.38	NA
23	3	0.26	5:31	11:45	21:36	NA	0.24	1.02	1.48	NA
24	3	0.26	5:46	12:29	21:36	NA	0.23	1.02	1.39	NA
25	3	0.27	5:46	12:29	21:36	NA	0.06	1.06	1.60	NA

frequently. Calves fed milk restrictively are known to perform frequent non-nutritive visits to the AMF, up to 12 times more than calves fed higher levels of milk, and especially when the milk allowance is gradually reduced in dairy calves (Vieira et al., 2008; De Passilleé et al., 2011). This may explain why the calves in this study decreased the numbers of their activity peaks when moved from two to three times milk allowance per day, and these fewer activity peaks could in fact tentatively point to higher levels of satiety and hence a higher welfare. The idea that calves were more satiated after 21 weeks is in line with the sudden drop in the height of the first activity peak between week 21 and 25. Calves at this later stage had a higher and more frequent milk replacer intake during the day and were therefore potentially less hungry and hence less eager to access to the AMFs when the first feeding session started, around 4 h in the morning, which is a time when calves are typically less active. In addition, with three milk timeslots instead of two (each session lasted between 5 and 6 h), calves had short waiting time in between the milk timeslots, especially between the second and third milk feeding session. As a result, calves had access to AMFs with longer time window and could drink more milk, we assume that this potentially meant that calves could avoid the "rush hour" at the starting of the milk feeding sessions with a restricted feeding routine.

In our study, most management procedures took place in the morning after the supply of the solid feed (at around 8:30 h). The second peaks between week 8 and 20 had a more or less stable timing at group level (around 10:30 h). This second peak might to a large extent be caused by the farm management activities at this time, initializing activity in the calves.

We identified a relative stable final peak (i.e. the fourth peak between week 8 and 20, the third peak between week 21 and 25) just before dark (between 21:07 h and 21:36 h), and far from any kind of feeding moment, and closer in terms of height to the second peak between week 8 and 20 and 21 and 25 on the respective weeks. We speculated that the last peaks were due to calves' need to express their natural behaviours, e.g. grazing at night (Kilgour, 2012) and play behaviour before dark (Jensen et al., 1998). A similar peak in calf activity just before dark, specifically around 20h00 and 22h00 was also reported by Webb et al. (2014), in terms of percentage of calves standing at a given time. In this study, we did not observe the behaviour of our calves manually, so we cannot conclude that the calves spent more time playing or orally manipulating the environment (potentially mimicking grazing). Other factors, e.g. ambient temperature, food availability, etc, as discussed in Giannetto et al. (2022), might also explain these patterns to some extent. To further study the last peaks, we recommend incorporating video recordings of the behaviour as reference.

We observed a relative constant night activity level (between 21:00 h and 4:00 h), with a gradual increase in the last four weeks of the fattening period. When the grown calves are bigger and, consequently, the available space per calf in the pen is much lower. This may result over time in large groups of calves becoming seemingly more active throughout the fattening period as a result of increasing disturbances between animals linked to limited space. Alternatively, since the change in night-time activity was detected by our model from week 21 onwards, it might also be linked to the changing of the milk feeding routine. However, this warrants further research. We also identified the deviations of time of peaks on some weeks compared to the weeks prior and after, e.g. the timing of the first peak in week 14, the third time of peak on week 10, and the fourth time of peak on week 17. To explain these deviations, further analysis of the dataset is required, for example, combining the feeding behaviour obtained from AMFs and the detailed farm management activities registered in the logbook.

A medium AUC of the LOO was displayed from our fitted model predicting a calf being active. The model had a medium accuracy (a low sensitivity and high specificity) in its prediction of whether a calf was active or not at any given time, suggesting that the predicted activity accounted for a low percentage of the truly active calves (i.e. low sensitivity), while the predicted inactivity was close to the true inactivity (i.e. high specificity). Although the low sensitivity may suggest that the model was not good at predicting when a calf was active, the high specificity of the model concerning inactivity might be useful for further detecting a sick calf because increased inactivity (i.e. lying time) is often seen in a sick calf (Lowe et al., 2019, Swartz et al., 2020). Activity also changes in a sick calf, e.g. standing time, however standing up is often triggered with the relatively low number of feeding moments (Pillen et al., 2016). Further work is needed to improve the accuracy, especially the sensitivity of the model in its prediction of whether an individual calf is active or not. In a sick calf, we might expect to observe either a missing peak (reduction in frequency of activity) or a reduction in activity compared to the group patterns. Moreover, individual variation should also be considered when identifying the individual activity patterns deviating from the group activity patterns. The individual patterns of activity of a calf could be related to many factors other than sickness, e.g. the dominance/weight or personality (Foris et al., 2019; in pigs: Bus et al., 2024). Further study should look into the range of individual variations of the normal activity patterns, for example, the relationship between individual number of AMFs visit and the reduced number of visits to AMFs in a sick calf.

In this study, we applied a binary activity variable to fit the model. Further studies should look for a predictive model that can fit a three-category activity variable (i.e. distinguishing standing, walking, and lying time), which can reflect a more detailed activity pattern of a healthy calf. In addition, further study should look for models fitting the discreet variables (i.e. step counts, number of lying bouts) from the current dataset, as step counts (Pillen et al., 2016) and number of lying bouts (Swartz et al., 2020) were reported to be important indicators for detecting sickness in a calf. To further develop a disease detection model, feeding information should also be included, as suggested by other studies (Bowen et al., 2021; Conboy et al., 2021; Lowe et al., 2021; Cantor and Costa, 2022).

It should be noted that the present study was carried out on a system where calves were group-housed in large pens but with the minimum required space allowance of 1.8 m^2 per calf. EFSA, however, recently recommended 3 m^2 per calf to allow for the expression of play behaviour, as well as smaller group sizes, i.e. between 2 and 7 (EFSA AHAW Panel (EFSA Panel on Animal Health and Animal Welfare), 2023). We recommend further research should hence investigate the activity patterns of calves kept in such an EFSA-recommended system.

5. Conclusion

We conclude that the activity pattern of healthy group-housed calves, corrected for trends over time, can be described by a binomial logistic model of the pattern changes over weeks, with a moderate predictive performance. Interesting features to extract from such activity patterns include the number and timing of peaks, as well as the proportion of night-time activity. These features clearly present the feeding management, and more specifically, meaningful deviations from the pattern may correspond to health or welfare issues in calves.

CRediT authorship contribution statement

Dengsheng Sun: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gwenaël G.R. Leday:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **C.G. van Reenen:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **P.P.J. van der Tol:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Laura E. Webb:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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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Contributions

Each author declares substantial contributions through the following:

(1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content,

Please indicate for each author the author contributions in the text field below. Signatures are not required.

Dengsheng Sun – 1,2
Gwenaël Leday - 1
Rik van der Tol – 1,2
Laura Webb – 1,2
Kees van Reenen – 1,2

Appendix 1. Weekly average summary of daily activity in healthy calves

Week of age	Standing time (%)	Lying time (%)	Walking time (%)	Number of steps	Number of lying bouts
8	27.6	68.5	3.9	5040	19
9	28.9	67.5	3.6	4754	18
10	28.5	67.9	3.6	4775	19
11	29.3	67.1	3.6	4780	18
12	30.0	65.9	4.1	5311	20
13	29.3	66.9	3.8	5047	20
14	29.5	66.6	3.9	5186	19
15	29.3	66.7	4.0	5230	19
16	29.4	66.5	4.1	5374	20
17	29.9	66.1	4.0	5261	20
18	31.4	64.2	4.4	5719	20
19	31.0	64.8	4.2	5566	21
20	31.2	64.3	4.5	5841	21
21	31.6	63.6	4.8	6120	21
22	31.4	63.8	4.8	6168	21
23	31.6	63.7	4.7	6051	22
24	32.3	63.0	4.7	6065	21
25	32.4	63.0	4.6	6000	21

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