Feeding behaviors collected from automated milk feeders were associated with disease in group-housed dairy calves in the Upper Midwest United States

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ABSTRACT

Automated milk feeders (AMF) are an attractive option for producers interested in adopting practices that offer greater behavioral freedom for calves and can potentially improve labor management. These feeders give farmers the opportunity to have a more flexible labor schedule and more efficiently feed group-housed calves. However, housing calves in group systems can pose challenges for monitoring calf health on an individual basis, potentially leading to increased morbidity and mortality. Feeding behavior recorded by AMF software could potentially be used as an indicator of disease. Therefore, the objective of this observational study was to investigate the association between feeding behaviors and disease in preweaning group-housed dairy calves fed with AMF. The study was conducted at a dairy farm located in the Upper Midwest United States and included a final data set of 599 Holstein heifer calves. The farm was visited on a weekly basis from May 2018 to May 2019, when calves were visually health scored and AMF data were collected. Calf health scores included calf attitude, ear position, ocular discharge, nasal discharge, hide dirtiness, cough score, and rectal temperatures. Generalized additive mixed models (GAMM) were used to identify associations between feeding behavior and disease. The final quasibinomial GAMM included the fixed (main and interactions) effects of feeding behavior at calf visit-level including milk intake (mL/d), drinking speed (mL/min), visit duration (min), rewarded (with milk being offered) and unrewarded (without milk) visits (number per day), and interval between visits (min), as well as the random effects of calf age in regard to their relationship with calf health status. Total milk intake (mL/d), drinking speed (mL/min), interval between visits (min) to the AMF, calf age (d), and rewarded visits were significantly associated with dairy calf health status. These results indicate that as total milk intake and drinking speed increased, the risk of calves being sick decreased. In contrast, as the interval between visits and age increased, the risk of calves being sick also increased. This study suggests that AMF data may be a useful screening tool for detecting disease in dairy calves. In addition, GAMM were shown to be a simple and flexible approach to modeling calf health status, as they can cope with non-normal data distribution of the response variable, capture nonlinear relationships between explanatory and response variables and accommodate random effects.

Key words: dairy calf, feeding behavior, automatic milk feeder

INTRODUCTION

In the United States, the majority of preweaning dairy calves are housed individually. This management strategy is due to the perception that housing calves individually can minimize the risk of disease, as it reduces calf-to-calf contact (von Keyserlingk and Weary, 2011). A recent survey conducted by USDA concluded that the most prevalent causes of morbidity and mortality in preweaning dairy calves are diarrhea and respiratory disease (Urie et al., 2018). Dairy calves are the future replacement cows of the herd; therefore, their health is vital to the overall success and productivity of the farm. The literature suggests that calf diarrhea or respiratory infection within the first 90 d of life is associated with greater age at calving and reduced performance later in life (Waltner-Toews et al., 1986; Correa et al., 1988). A calf diagnosed with one disease (e.g., diarrhea or bovine respiratory disease) can cost over $100 more to rear than a calf never diagnosed as sick (Mohd Nor et al., 2012). Calfhood history of pneumonia or scours is associated with premature death and increased risk of culling (Waltner-Toews et al., 1986), resulting in further economic losses for the producer. Since group-housed calves share a common space, disease transmission can be greater in these systems compared to calves housed...
individually (Losinger and Heinrichs, 1997; Gulliksen et al., 2009). However, calves housed in groups had greater feed intake and weight gain during the prewean- ing period (Miller-Cushon and DeVries, 2016) and postwean- ing period (De Paula Vieira et al., 2010; Costa et al., 2014). Producers are interested in exploring housing options that are preferred by consumers and that allow calves greater behavioral freedom in addition to perceived affective state and performance benefits of social housing (von Keyserlingk et al., 2009). Therefore, it is vital that producers have efficient management tools to identify sick animals at an early stage while keeping the improved welfare conditions associated with group- housed calves.

One potential solution to individually monitor calves in group housing systems is an automated milk feeder (AMF), which can be used to feed preweaning dairy calves (Boe and Færevik, 2003; Hepola, 2003). Produc- ers are attracted to AMF due to the economic benefits, such as increased ADG of calves and improved labor flexibility (Janssens et al., 2016). Additionally, produc- ers invest in AMF to offer more milk to calves without increased labor input (Kung et al., 1997), improving working conditions for calf caretakers, raising calves that are able to partake in natural behaviors, and therefore, improving both calf and worker well-being (Medrano-Galarza et al., 2018b). However, it is possible that allowing calves access to a group pen with an AMF at a young age (<24 h after birth) could potentially heighten the risk of disease, therefore, creating additional human labor requirements (Medrano-Galarza et al., 2018a). The AMF are an attractive management tool because they offer a gradual weaning program, which has been shown to be preferable to abrupt wean- ing (Sweeney et al., 2010) and reduces excessive stress on calves (Hnatiuic and Caracostea, 2017). Because the AMF is reliable and relatively low maintenance (Hna- tiuic and Caracostea, 2017), it allows for a more flexible labor schedule and savings in the cost of hired labor (de Jong et al., 2003). Lastly, the AMF offers welfare benefits for the calf including milk delivery via a nipple at volumes and frequencies more similar to suckling from a dam, in turn more natural for the calf (De Paula Vieira et al., 2008).

The AMF station identifies calves on an individual basis by reading the calf’s unique radio-frequency identification tag. These stations record individual calf vis- its to the feeder as a rewarded visit or an unrewarded visit. Rewarded visits are defined as the visits to the AMF with milk meal offered (i.e. the calf is entitled to drink at that time) and unrewarded visits are defined as visits to the AMF without milk offered, which is determined by the programmed feeding allowance. The AMF has the capability of delivering milk to calves in predetermined portions, which allows calves the ability to feed throughout the day and not in a singular visit. The feeder software program records feeding behaviors, such as milk intake (mL/d) and drinking speed (mL/ min) by visit, duration of the visit (min), as well as re- awarded and unrewarded visits (count/d) for each indi- vidual calf. The software program uses an algorithm to alert the farmer when a calf’s daily milk intake average deviates or reduces from previous intake, suggesting the calf may be a suspect for illness. Even though the AMF software has the capability of comparing calves’ daily intake to their rolling average, there is reason to believe that the software algorithm lacks the timeliness and sensitivity to detect disease events in some calves (Knauer et al., 2017).

Calf score events, expressed as the number of calves identified as sick over the total number of calves on the farm, follow a binomial process. Binomial response variables, with an assumed underlying distribution, can be analyzed using generalized linear models, an example of this would be a logistic regression (Nelder and Wedderburn, 1972). This methodology uses a logistic scale with a linear predictor to describe the relationship between the response variable and covariates, which would be applied to the weekly preweaning health scores and feeding behaviors (Hastie and Tibshirani, 1986). Previous literature suggests that generalized additive models are ideal for accommodating nonlinearity between explanatory and response variables, therefore, making it an attractive option for analyzing calf health status and behavior data since these can present nonlinear relationships (Wood, 2017). Since the model incorporates both fixed effects of number of rewarded and unrewarded visits, total milk intake, drinking speed, interval between visits, visit duration, and age and random effects of calves, it is considered a generalized additive mixed model (GAMM; Hastie and Tibshirani, 1986; Wood, 2017). This analysis is appropriate for the current study because it can capture hidden relationships that simple linear models cannot detect, in turn leading to loss of biological relationships. Therefore, the objective of this study was to investigate the association between feeding behaviors and disease in preweaning dairy calves fed with AMF in typical field conditions at a single study site dairy farm using a GAMM approach.

**MATERIALS AND METHODS**

The use of animals in the study was approved by the University of Minnesota’s Institutional Animal Care and Use Committee (protocol no. 1806–36043A).
**Animals, Management, and Feeding**

This study was conducted at a dairy farm located in the Upper Midwest of the United States with approximately 2,500 Holstein cows. On-farm data collection was performed from May 2018 to May 2019, capturing all seasons and a large sample size (n = 763 heifer calves). After birth, heifer calves were placed in individual indoor, climate-controlled hutches until approximately 7 d of age. Calves were fed pasteurized colostrum within 6 h of birth. In individual indoor hutches, calves were bottle-fed 2 L of milk replacer twice per day (4 L/d total), and water was provided ad libitum. Once calves reached approximately 7 d of age, they were moved to 1 of the 12 group pens until weaning at 56 d of age. Calves remained in the same group throughout the entire preweaning stage.

The groups consisted of 15 calves each and the age difference between the youngest and oldest calves in the group did not exceed 1 wk. The 6 AMF (DeLaval Calf Feeder CF1000S, DeLaval) fed calves a combination of whole milk (50%) and milk replacer (50% concentration equating to 150 g of milk replacer powder added to 0.25 L of water). Calves were also offered pelleted starter and water ad libitum.

Each AMF fed 2 pens of calves, with 1 feeding station per pen. Once calves started on AMF, allowance started at 5 L/d and increased to 6.5 L/d over a 7-d period. Then, milk allowance gradually increased from 6.5 to 7.5 L/d over a 14-d period. Allowance peaked at 9 L/d per calf at d 35 and stayed at 9 L/d for 18 d. The weaning process began at 46 d of age stepping-down milk allocation by 0.90 L/d (over a 10-d period) reaching zero at 56 d of age.

Calves were housed in 11 × 11 m pens with a 3.7 m wide non-bedded area in the front of the pen where calves had access to the AMF station, water trough, and starter at a feedbunk. The group pen had a resting area of 5.4 m² per calf and this resting area was bedded with sawdust during the summer and straw during the winter. Therefore, each calf had a total space allowance of approximately 9 m². The ventilation system in the barn used a combination of tubes, exhaust fans, and side curtains.

**Feeding Behavior**

Daily feeding data recorded by the software Institute Program (Förster-Technik) was downloaded on a weekly basis, which included the calf identification, beginning and end of each visit (timestamp), if the visit was rewarded or unrewarded, milk allowance per visit (mL), cumulative milk consumption for each d (mL), drinking speed (mL/min), and sudden withdrawal from rationed meal (breakaway). The data were extracted from all AMF when no calves were present at the AMF partaking in a meal. Due to a brief loss of contact between the receiver on the AMF and the transmitter on the calf’s ear, multiple instances for the same visit at the AMF were generated by the software. To create a single visit from multiple instances we adopted the following procedure: (1) multiple instances were grouped to a single instance if the interval between instances were lower than 30 s, and the cumulative milk consumption was the same; (2) instances within the same visit with different milk allowance were excluded from the data set; (3) instances with drinking speed greater than 0 and cumulative milk consumption equal to 0 were excluded; (4) a visit at the AMF was considered as a single visit when the interval between instances was lower than 2 min (according to manufacturer’s instruction).

After preprocessing the data set in R (R Core Team, 2020), we created the feeding behavior variables evaluated in this study including: (1) total milk intake (mL/d); (2) average intake/visit (total milk intake divided by number of visits to the milk feeder with reward; mL); (3) drinking speed (average daily drinking speed; mL/min); (4) interval between visits [average daily interval between visits (both rewarded and unrewarded) to the AMF; min]; (5) visit duration [average daily length of visits to the milk feeder; min]; (6) number of rewarded visits (daily visits to the AMF in which there was milk consumption); (7) number of unrewarded visits (daily visits to the milk feeder in which there was not a consumption); (8) calf age (number of days from birth to the day of health score assessment). Milk allowance per visit and sudden withdrawal from rationed meal, as well as the behaviors derived from them, were not considered in the current study. Such variables were not included in the study because failures in the AMF system resulted in uncorrected data annotation, generating bias in the data set. As the animals were placed in the AMF during different times of the day (morning or evening) the first day of data at the AMF was removed from the data set. In addition, the last day of data (i.e., weaning day) was removed from the raw data set due to differences in time of last meal of the weaning program. In addition, drinking speed >2,000 (mL/sec), number of rewarded visits >1,000 (mL/sec), cumulative milk consumption equal to 0 were excluded; (3) instances with drinking speed greater than 0 and cumulative milk consumption equal to 0 were excluded; (4) a visit at the AMF was considered as a single visit when the interval between instances was lower than 2 min (according to manufacturer’s instruction).

**Health Score**

Calf health scoring was performed once per week by a single trained observer throughout the entire study for
improved consistency. Intra-observer reliability testing was completed by having the single trained observer and a veterinarian co-author in the study assessing all calves randomly approximately every 2 mo throughout the 12-mo study period and comparing results. Agreement was greater than 95% for individual scores. A method adapted from McGuirk (2008) and Jorgensen et al. (2017) was used. This method assessed health status by scoring calf attitude, ear position, ocular discharge, nasal discharge, hide dirtiness, cough score, and rectal temperatures. Scores were assigned on a scales of 0 to 2, 0 to 3, and 0 to 4. A score of 0 indicated a healthy animal and a higher score indicated a more ill animal. Attitude was scored on a 0-to-4 scale, with 0 = active, 1 = quiet/dull, 2 = depressed, 3 = nonresponsive, and 4 = dead. The attitude score was used to determine how calves related to the human observer. Ear position was scored on a 0-to-4 scale, with 0 = no ear droop, 1 = unilateral ear droop, 2 = slight bilateral ear droop, 3 = severe bilateral ear droop, and 4 = head tilt. Cough was scored on a 0-to-3 scale, 0 = no cough, 1 = a single spontaneous cough, 2 = 2 spontaneous coughs, and 3 = more than 3 spontaneous coughs. Ocular discharge was scored on a 0-to-3 scale, 0 = no discharge, 1 = mild ocular discharge, 2 = moderate amount of bilateral discharge, and 3 = heavy ocular discharge. Nasal discharge was scored on a 0-to-3 scale, 0 = normal serous discharge, 1 = small amount of unilateral or cloudy discharge, 2 = bilateral or cloudy or excessive mucus, and 3 = copious or bilateral mucopurulent nasal discharge. Hide dirtiness score of the perianal region, underside of the tail, and tailhead of each calf was scored as an indirect assessment of diarrhea, on a scale of 0 to 2 (adapted from Jorgensen et al., 2017), 0 = clean, 1 = evidence of loose or abnormal fecal consistency, and 2 = significant evidence of watery diarrhea. This modified method was considered preferable for group housing scoring because the limited area scored increased the likelihood that the fecal material observed was from the calf. In addition, this method has been adapted and modified to create a robust scoring system to accurately assess hygiene of calves to monitor herd health with high observer agreement (Kellermann et al., 2020). However, we also acknowledge that some amount of fecal material on the calf could be from the environment or previous days and potentially bias the results. Rectal temperatures were recorded for calves scoring ≥2 on any health category because this was defined as abnormal according to previous literature (McGuirk, 2008).

Calves with a cumulative score ≥3 as the sum of all health category scores (attitude, ear position, ocular discharge, nasal discharge, hide dirtiness, cough score) were categorized as sick, whereas calves scoring less than sum of 3 were categorized as healthy. The final data set included 3,003 health scores of 599 calves (Figure 1A–1C; Table 1). This was accomplished by down sampling (randomly) the data set to have an approximately equal number of observations in each health category (i.e., healthy and sick), and excluding calves older than 75 d. These latter calves were on restricted intakes during the weaning process or recovering from long periods of sickness.
**Statistical Analyses**

Weekly preweaning health category (0 = healthy and 1 = sick), were considered as response variables \(y_i\), whereas feeding behaviors were the linear covariates \(X\) in this study. The assumption for the response variable \(y_i\) \((i = 1, 2, 3, \ldots, n)\) is that it follows an exponential family probability distribution with mean \(\mu_i = E(y_i)\) and scale parameter \(\varphi\) \(\{\text{i.e., } y_i \sim \text{EF}(\mu_i, \varphi)\}\). Health score events were modeled as \(y_i \sim \text{Binomial}(n_i, \pi_i)\), where \(n_i\) is the \(i\)th health score event, and \(\pi_i\) is the probability of sick events for the \(i\)th health score event. Generalized additive mixed model was used to accommodate the response variable \(y_i\) where the linear predictor is represented as: \(g(\mu_i) = a_1 \theta + \sum_{j=1}^g f_j(x_{ij})\), where \(g\) is a known link function, \(a_i\) is the \(i\)th row of an incidence matrix, \(\theta\) is the vector of corresponding parameters, and \(f_j\) is the \(j\)th unknown smooth function of covariates \(x_{ij}\) \(\{\text{i.e., reduced rank smoothing splines; Wood et al., 2017}\}\). Random effects can be accommodated in a GAMM by defining the model in an empirical Bayesian approach \(\{\text{Wood, 2017}\}\). Such framework makes possible the inclusion of a uniform and Gaussian prior distribution for \(\alpha\), \(\beta\), \(\sigma\), \(\varphi\), \(\lambda\), and \(\mu\) \(\{\text{Passafaro et al., 2019}\}\). A quasilikelihood approach was considered to accommodate potential overdispersion in the data, because the variance of the binomial distribution is a function of its own mean. Further details related to generalized additive model can be found in \(\{\text{Wood (2011, 2017) and Passafaro et al. (2019)}\}\).

The GAMM was fitted including the fixed effects of number of rewarded and unrewarded visits, total milk intake, average intake/visit, drinking speed, interval between visits, visit duration, and age. Calf was included as random effect in the model and calf was nested within pen. Health scores were analyzed on a weekly basis independent of each other plus accounting for age in the model. The random effect is as follows: \(\alpha_{j(i)} \sim \mathcal{N}(0, \Sigma)\), where \(\Sigma\) is the co-variance matrix accounting for the dependence structure. Interaction between all fixed effects were introduced to the model by considering the statistical significance of an interaction. If the interaction was statistically significant \((P < 0.05)\) it was added, otherwise the interaction was removed from the model. Due to the amplitude and different units across the linear covariates, they were scaled to display mean 0 and variance 1. For all linear covariables and interactions, reduced ranking smoothing cubic spline function was used to fit the final GAMM, which can be described as follows:

\[
\begin{align*}
\left\{ y_i \mid \alpha_{j(i)} \right\} & \sim \text{Binomial}(n_i, \pi_i, \varphi) \\
\text{logit}(\pi_i) & = r_i + u_i + \alpha_{j(i)} + \sum_{b=1}^9 s_{mb}(m_i) \beta_{mb} + \sum_{c=1}^9 s_{hc}(f_i) \beta_{hc} \\
& + \sum_{e=1}^9 s_{ve}(v_i) \beta_{ve} + \sum_{g=1}^9 s_{dg}(d_i) \beta_{dg} + \sum_{h=1}^9 s_{ah}(a_i) \beta_{ah} \\
& + \sum_{l=1}^{25} \sum_{n=1}^{74} \beta_{mln} s_{ml}(m_i) s_{jl}(f_i) s_{nl}(n_i) \\
& + \sum_{l=1}^{9} \sum_{z=1}^{9} \beta_{mzl} s_{ml}(m_i) s_{zl}(f_i)
\end{align*}
\]

where \(\text{logit}(\pi_i)\) is the link function, defined as \(\text{logit}([\pi_i/(1 - \pi_i)])\); \(r_i\) is the fixed effect of number of rewarded visits; \(u_i\) is the fixed effect of number of unrewarded visits; \(s_{mb}(m_i)\), \(s_{hc}(f_i)\), \(s_{ve}(v_i)\), \(s_{dg}(d_i)\), and \(s_{ah}(a_i)\) are the reduced ranking cubic splines function with respectively knots \((i.e., b, c, e, g, and h)\) for total milk intake \((m_i)\), feed (drinking) speed \((f_i)\), interval between visits \((v_i)\), visit duration \((d_i)\), and age \((a_i)\), respectively; \(\beta_{mb}\), \(\beta_{hc}\), \(\beta_{ve}\), \(\beta_{dg}\), and \(\beta_{ah}\) are the regression coefficients for total milk intake, feeding speed, interval between visits, visit duration, and age, respectively; \(\beta_{mzl}\) is the regression coefficient for the interaction between number of rewarded visits and total milk intake, which \(s_{jl}(f_i)\) and \(s_{ml}(m_i)\) are the corresponding tensor product of the cubic splines function with knots \(l\) and \(n\); \(\beta_{v, f, e}\) is the regression coefficient for the interaction between num-

### Table 1. Descriptive statistics for the numeric predictor variables observed on 599 preweaning dairy calves (from d 7 to 56 of age) representing 3,003 calf score events (1,892 healthy and 1,111 sick) fed with automated milk feeders on a farm in the Upper Midwest of the United States

| Variable                        | Mean   | SD      | Minimum | Maximum |
|---------------------------------|--------|---------|---------|---------|
| Total milk intake (mL/d)        | 6.446  | 2.306   | 0.0     | 10.947  |
| Average intake/visit (mL)      | 1.865  | 0.576   | 0.0     | 3.000   |
| Drinking speed (mL/min)        | 811.2  | 331.4   | 0.0     | 1.852.8 |
| Interval between visits (min)  | 142.4  | 125.7   | 14.2    | 989.7   |
| Visit duration (min)           | 1.8    | 3.1     | 0.2     | 10.9    |
| Age (d)                        | 38.5   | 15.9    | 7.0     | 75.0    |
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Table 2. Parameter estimates and approximate significant level of smooth terms on behavioral indicators of health status of 599 preweaning dairy calves (from 7 to 56 d of age) fed with automated milk feeders on a farm in the Upper Midwest of the United States.

| Parameter                                      | Estimate | SE  | OR (CI)² | RDF³ | EDF⁴ | P-value |
|------------------------------------------------|----------|-----|----------|------|------|---------|
| Intercept                                      | −0.973   | 0.204 | 0.378 (0.253, 0.564) | <0.0001 |      |         |
| Visit with rewards                             | 0.123    | 0.040 | 1.131 (1.045, 1.224) | 0.0024 |      |         |
| Visit without rewards                          | −0.005   | 0.008 | 0.995 (0.980, 1.010) | 0.5345 |      |         |

1 Generalized additive mixed model representing 3,003 calf score events (1,892 healthy and 1,111 sick).
2 OR = odds ratio; confidence interval of OR provided in parentheses.
3 RDF = reference number of degrees of freedom.
4 EDF = effective degree of freedom.

RESULTS

Descriptive Statistics of Health Status and AMF Feeding Data

Feeding behaviors were analyzed for 599 calves representing 3,003 calf score events on the AMF during the milk-fed period (Table 1). Of the 3,003 calf scores, 1,892 healthy and 1,111 sick events were observed (Figure 1A).

Calves consumed on average 6,446 (±2,306; SD) mL/d and averaged 1,865 (±575.3) mL of milk per visit. Calves were 38.5 (±15.9) d of age when receiving full milk allowance (9 L). Calves in our study had a drinking speed of 811.2 (±331.4) mL/min, feeding for 1.8 (±3.1) min per visit, with intervals between visits to the AMF of 142.4 (±125.7) min. More detailed results are shown in Table 1. Figures 1B and 1C show the distribution of rewarded and unrewarded visits, respectively.

Associations Between Feeding Behaviors and Calf Health

Total milk intake (mL/d) was associated with dairy calf health status (P < 0.0001, Table 2; Figure 2A). This result indicates that as milk consumption increased, the risk of calves being sick decreased, suggesting that calves experiencing sickness were consuming less than their healthy counterparts. Average intake/visit was removed from the final model, as it was not statistically significant. Drinking speed (mL/min) was another behavioral indicator of dairy calf health status (P < 0.0001, Table 2; Figure 2B). Results indicate that as drinking speed increased, the risk of calves being sick decreased, suggesting that calves experiencing sickness were drinking slower than their healthy counterparts. The interaction between intake and drinking speed was associated with calf health status (P = 0.0264, Table 2). For example, if a calf had a drinking speed over 800 mL/min, their risk of sickness decreased with total milk intake per day below 7,000 mL (Figure 3). In addition, if a calf displayed a drinking speed below 800 mL/min, its risk of sickness decreased with total milk intake per day above 7,000 mL (Figure 3). Results from this study suggest a complex relationship between calf health status, total milk intake per day, and drinking speed.

Regarding meal patterns, interval between visits (min) to the feeder was associated with dairy calf health status (P = 0.0264, Table 2). For example, if a calf had a drinking speed over 800 mL/min, their risk of sickness decreased with total milk intake per day below 7,000 mL (Figure 3). In addition, if a calf displayed a drinking speed below 800 mL/min, its risk of sickness decreased with total milk intake per day above 7,000 mL (Figure 3). Results from this study suggest a complex relationship between calf health status, total milk intake per day, and drinking speed.

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Calf health status was associated with age ($P < 0.0001$; Table 2; Figure 2D). In this study, as age increased, the risk of calves being sick increased, suggesting that older calves were more likely to experience sickness compared with their younger counterparts in the system used in the current study.

Dairy calf health status was positively associated with rewarded visits ($P = 0.0024$, Table 2). As the number of rewarded visits to the AMF increased, the risk of calves being sick increased. The interaction between rewarded visits and total milk intake was associated with calf health status ($P = 0.0011$, Table 2). For example, if a calf consumed less than 6000 mL/d, the risk of sickness decreased with number of rewarded visits above 7 (Figure 3). There was a complex relationship between calf health status, total milk intake per day, and number of rewarded visits in the current study. The interaction between rewarded visits and interval between meals was associated with calf health status ($P = 0.0011$, Table 2). For example, if a calf’s interval between visits spanned 100 to 900 min, their risk of sickness decreased with rewarded visits below 2 (Figure 3). In addition, if a calf’s interval between visits was less than 60 min, their risk of sickness decreased with 6 or more rewarded visits. This was another complex relationship found between calf health status, interval between visits, and number of rewarded visits.

Figure 2. Predicted health status of dairy calves on the odds ratio scale for each significant cubic spline smoothing functions of total milk intake (A), drinking speed (B), interval between visits (C), and age (D) for 599 preweaning dairy calves (from 7 to 56 d of age) fed with automated milk feeders on a farm in the Upper Midwest of the United States.

Figure 3. Predicted health status of dairy calves on the odds ratio scale for the significant interaction number of rewarded visits × total milk intake (A), number of rewarded visits × interval between visits (B), and total milk intake × drinking speed (C) for 599 preweaning dairy calves (from 7 to 56 d of age) fed with automated milk feeders on a farm in the Upper Midwest of the United States.
DISCUSSION

Calf Management

This observational study was conducted in a convenience sample of a single commercial dairy farm in the Upper Midwest, therefore, there was uniformity in management practices and housing. Previous studies were conducted at multiple farms, had a small sample size, or were conducted in countries other than the US. Beyond the farm’s large sample size and willingness to participate in the study, the farm was chosen due to having management practices similar to the previously identified industry practices (Jorgensen et al., 2017), which could make the results of the current study more generalizable to Midwest producers. The average feeding plan on our study farm included a 7-d background period where calves were manually fed their milk. After that time, they were introduced to the group pen, with an average ramp up period of 21 d, a hold period of 18 d, and a ramp-down period of 10 d, with amount of milk offered during the hold period of 9 L/d. This is a similar milk allowance of other dairies in the Upper Midwest, as Jorgensen et al. (2017) reported an average peak allowance of 8.3 ± 2.0 L (range: 5–15 L). In addition, calves were fed by the AMF for 49 d, which was similar to industry practices in Upper Midwest farms, as Jorgensen et al. (2017) reported calves spent 52.1 ± 7.5 d (range: 40–79 d) on the AMF.

Regarding calf housing practices, calves in this study were housed in individual hutches before entrance to the group pen at 7 d of age; that was similar to most facilities in the Upper Midwest, which reported housing calves individually until 5.1 d of age on average (range: 0–14 d; Jorgensen et al., 2017). Grouping approach has also been reported to be associated with calf health status. Our study farm kept the groups together throughout the study period and did not introduce new calves to the groups. Research has suggested negative welfare consequences of regrouping, such as reductions in lying time (Horvath and Miller-Cushon, 2018). Therefore, our results may not be generalizable to farms that continuously introduce calves to housing groups. Repeated social regrouping and relocation of calves have inconsistent results. Some studies reported that older calves are generally larger, therefore, they are more dominant at the feed access point (Warnick et al., 1977) disrupting behaviors in the hours and days following regrouping (von Keyserlingk et al., 2008). However, other studies reported that no clear evidence exists that changing groups stresses calves (Veissier et al., 2001) and repeated regroupings had little effect on subsequent social behavior of calves (Raussi et al., 2005). This approach was atypical of other facilities in the Upper Midwest, as most farms in the Upper Midwest (82.4%) used a dynamic stocking approach in which new calves are continuously introduced to the group of existing calves on a single AMF (Jorgensen et al., 2017).

Another factor that may create stresses for calves is group size. It is recommended that calves be housed in small groups of 10 or fewer to reduce incidence of disease (Svensson and Liberg, 2006). In our study, calves were housed in groups of 15. Jorgensen et al. (2017) reported that the average group size for farms in the Upper Midwest was 17.8 calves, and few farms stocked calves in large groups (25–30). Calves housed in large groups had a higher incidence of respiratory illness and lower ADG (Svensson and Liberg, 2006), increased odds of higher nasal score (Jorgensen et al., 2017), increased cases of severe diarrhea (Losinger and Heinrichs, 1997), and higher morbidity and mortality (Van Putten, 1982). However, these effects can be counterbalanced by other management practices that can alter health outcomes (Rushen et al., 2008). Other studies have determined discrepancies in these findings and reported no differences in diarrhea prevalence in preweaning dairy calves housed in a large group setting (Svensson et al., 2003; Svensson and Liberg, 2006). Additionally, housing calves in large groups creates more competition for access to the AMF (Jensen, 2004). The average age range between the oldest and youngest calves housed in the same group pen in our study was up to 7 d, which is a smaller age range than the Upper Midwest average of a 21.7 d difference (ranging from 2.1- to 70-d age difference; Jorgensen et al., 2017). A large age range between calves can be concerning due to previously mentioned reasons of increased competition.

Associations Between Feeding Behaviors and Calf Health

The results of the current study are consistent with other work suggesting an association between calf health status and feeding behaviors (Svensson and Jensen, 2007; Knauer et al., 2017; Morrison et al., 2021); however, results are dependent on milk feeding strategy (Jasper and Weary, 2002; Borderas et al., 2009; Costa et al., 2021). Previous research suggests that in calves fed low allowances of milk, illness may have limited effects on feeding behaviors because commercial quantities are well below ad libitum quantities (Jasper and Weary, 2002). Research suggests that calves fed 4 to 6 L/d have no reduction in milk intake but have lower feeding motivation and reduced the number of visits to the AMF (Svensson and Jensen, 2007; Borderas et al., 2009). The calves in our study were fed a similar allowance (9 L/d) to the industry standard of calves fed milk.
by AMF in the Upper Midwest of 8.3 ± 2.0 L (range: 5–15 L; Jorgensen et al., 2017). It is reasonable to assume that we were able to detect associations between feeding behavior and calf health events due to the milk allowance in the current study.

Reduction in feeding behavior and metabolic activity are common responses to illness in dairy calves (Weary et al., 2009; Lowe et al., 2019). Research suggests that a decrease in overall activity serves as a survival tactic to conserve energy for necessary behaviors and immune defense mechanisms (Hart, 1988; Dantzer and Kelley, 2007). Our study supports prior evidence that sick calves display a reduction in feeding behaviors, performing high priority behaviors (e.g., rewarded visits) in a sickness event (Knauer et al., 2017; Sutherland et al., 2018). Similar to our study, previous research has reported associations between rewarded visits as they relate to calf health. Studies have found a decrease in visits to the feeder on the day of illness detection (Borderas et al., 2009; Knauer et al., 2017), >2 d before clinical signs of diarrhea (Sutherland et al., 2018; Lowe et al., 2019) and respiratory illness (Svensson and Jensen, 2007). In contrast, recent work suggests no associations between rewarded visits and calf disease (Conboy et al., 2021); however, this could be due to limitations in statistical analysis by using linear models. A more robust modeling approach, such as GAMM, could potentially capture relationships that were undetected in prior research (Passafaro et al., 2019). Similar studies have used multivariable generalized linear regressions to describe feeding behaviors and their relationship with calf health status (Knauer et al., 2017). However, GAMM have the potential to be more effective in modeling correlated and clustered responses with the capability of capturing repeated measures, such as behavioral data (Groll and Tutz, 2012). Our study did determine an association between rewarded visits and calf health status, with increased visits being an indicator of a sick calf. This could potentially be due to sick calves being displaced from the feeder more often than their healthy counterparts, increasing their daily visits to the feeder to finish their allotment. An interaction between rewarded visits and intake was determined, which could further explain this hypothesis of calf competition at the feeder (De Paula Vieira et al., 2008) and poor calf vigor (Zaremba et al., 1993) resulting from anorexia (Mee, 2004). In addition, our cutoff of summed health scores of 3 instead of a greater number could have included calves with more mild health problems in the sick category.

In the current study, there was no relationship between unrewarded visits and sickness. However, other work suggests an association between unrewarded visits and calf health status. For example, Rosenberger et al. (2017) found that unrewarded visits increased in frequency with decrease in daily milk allowance, therefore, being an indicator of hunger. Other studies suggest that unrewarded visits can be a sensitive feeding-behavior measure because they will decrease during illness events due to low biological necessity (Costa et al., 2021) and emotional state of the animals (Weary et al., 2009; Neave et al., 2013). Other research indicates that during the weaning period, calf age and unrewarded visits may be related. For example, De Paula Vieira et al. (2012) reported that the presence of older weaned companion dairy calves influence feeding behaviors of cohort calves before and after weaning from milk. More specifically, calves housed with an older companion made fewer unrewarded visits to the AMF compared with counterparts housed with a companion that was similar in age (De Paula Vieira et al., 2012). Regarding age, our study suggests that older calves were more likely to experience sickness compared with their younger counterparts. This could be attributed to attitude changes from sickness being more pronounced in older calves. In addition, older calves are more likely to experience bovine respiratory disease (33 d of age; Cantor and Costa, 2022), therefore, being more easily identifiable. However, this result was contrary to other studies reporting that older calves have a faster, more efficient, and more focused immune response compared with younger calves (Batista et al., 2012).

Multiple recent studies have also reported that calf sickness is associated with a reduction in total milk consumption on a daily basis (Sutherland et al., 2018; Belaid et al., 2020; Conboy et al., 2021; Morrison et al., 2021). However, fewer studies have reported specific feeding behaviors as reliable indicators of disease. Similar to our study, Cramer and Ollivett (2020) and Conboy et al. (2021) reported that sick calves drink slower than their healthy counterparts. Other research has reported a change in drinking speed before treatment for diarrhea and on the day of diagnosis of bovine respiratory diseases (Knauer et al., 2017; Morrison et al., 2021). In the current study, sick calves were consuming less per day and were drinking slower, which supports previous work suggesting a decrease in drinking speed for calves experiencing illness events (e.g., respiratory disease; Knauer et al., 2017; Conboy et al., 2021) with similar entry to the feeder (9 and 8 d of age, respectively) and age at weaning (56 d). However, behavioral changes could be attributed to differences in larger group size (e.g., 17 calves; Knauer et al., 2017) potentially leading to increased aggression. Calves on restricted diets with limited amount of milk had higher feeder occupancy due to greater number of unrewarded visits, therefore leading to higher competition at the feeder (De Paula Vieira et al., 2008). Additional behavioral findings by
De Paula Vieira et al. (2008) suggest that drinking milk more rapidly during an allotted visit is an indicator of hunger in dairy calves.

Regarding meal patterns, other research has reported that healthy calves have a minimum of 40 min intervals between milk meals (von Keyserlingk et al., 2004) with longer postmeal intervals associated with greater milk allowance (Senn et al., 2000). However, these findings could be attributed to smaller group size (3 calves and 11 calves, respectively) and low aggression in those studies. In addition to the smaller group size, the minimum time between feedings could also be dependent upon the setup of the AMF. To our knowledge, this is the first study to identify longer intervals between visits as an indicator of a calf sickness.

**Generalized Additive Mixed Models**

To our knowledge, this is the first study to investigate the application of GAMM techniques to study the relationship between feeding behaviors in preweaning dairy calves to detect disease. This methodology may shed light into hidden relationships traditionally explored using linear methods, given the capacity of GAMM to capture nonlinear relationships between explanatory and response variables while incorporating random effects in the model. Visual inspection of the model displayed a nonlinear pattern for covariates, such as interval between visits (min), total milk intake (mL/d), drinking speed (mL/min), and age (d; Figure 2). Furthermore, graphical inspection of the curves has the potential to determine regions in the curve where the risk of illness increases. Also, GAMM are beneficial to minimize instances of overfitting by optimizing a maximum likelihood estimation, therefore, potentially increasing the model ability to predict new observations (Wood, 2017). The proposed analytical approach can reveal important relationships between feeding behavior and calf health status, and yet generate potential predictors to be used as inputs in predictive models for early disease detection.

However, because regression models reflect associations between the explanatory and response variables, there is not necessarily a direct causal interpretation for the results and additional assumptions are needed (Rosa and Valente, 2013; Bello et al., 2018). Confounders not accounted for in the model can lead to spurious correlation limiting the effectiveness of the model and causal mechanisms. Nonetheless, previous research suggests that observational data coupled with causal interventions can be beneficial in improving management strategies on livestock operations. In the context of analyzing feeding behaviors of group-housed dairy calves on AMF, GAMM identified insightful associations between feeding behavior and calf health status.

**CONCLUSIONS**

The AMF was able to collect important behavioral traits that we identified as potential indicators of calf health status. The use of GAMM allowed the investigation of important relationships and interactions that may serve as key predictors to aid optimized decision-making tools through further development of modern analytical approaches (e.g., machine learning algorithms). Based on the associations found in our study, future research should evaluate the use of predictive models applied to longitudinal behavior data to early detect risk of diseases.

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