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Association of rumination with milk yield of early, mid and late lactation dairy cows

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Abstract: Identification of the associations of cow feeding behaviour with milk yield (MY) is important for supporting recommendations of strategies that optimize MY. The objective of this study was to identify associations between measures of rumination time (RT) and MY using data collated from 2 777 dairy cows on nine commercial dairy farms during the years 2017 to 2019. A database contained behaviour and daily MY data. Cows averaged (mean ± standard deviation) 2.7 ± 1.6 lactations, 153 ± 81 days in milk, and 23.2 ± 7.5 kg/day of MY during the observation period. Behavioural data included RT (504 ± 93 min/day), feeding time (FT) (479 ± 110 min/day), resting time (360 ± 94 min/day), and activity time (96 ± 45 min/day). The coefficient of variation for RT (min/day) was 18.5%. The behavioural differences observed in this study provide a new insight into the effects of RT and FT on MY. MY was positively associated with RT in early and mid-lactation dairy cows with correlation coefficients of 0.24 ($P < 0.001$) and 0.25 ($P < 0.001$), respectively. The mean level of rumination time (MRT) was shown to be correlated with total MY produced over the whole lactation (305 days). The differences in MY between the highest and lowest MRT groups of cows were 1 735 kg, 2 617 kg and 1 941 kg in the first, second and third lactation, respectively. High-yielding dairy cows in early (≥ 23 kg/day) and mid (≥ 30 kg/day) lactation achieved the highest RT (522 ± 3.54 min/day and 507 ± 3.17 min/day, $P < 0.05$) and the highest FT (457 ± 4.69 min/day and 496 ± 4.00 min/day, $P < 0.05$), respectively. Cows in the highest MY groups also had the lowest activity and resting times during the most productive (early and mid) phases of lactation ($P < 0.05$), which is in agreement with our finding that more productive cows spend a greater proportion of their time feeding and ruminating.

Keywords: accelerometer; behaviour; MilkBot model; Levenberg-Marquardt algorithm; precision dairy farming; MooMonitor+

Dairy cows are a foregut fermenting species and thus, rumination is a natural behaviour, a unique, defining characteristic of ruminants and a proven direct indicator of cow wellbeing (Kaufman et al. 2018). Rumination is the process of regurgitation, remastication, salivation and swallowing of ingesta

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(Beauchemin 2018). Rumination and eating are the main ways in which feed is reduced in particle size. However, mastication is slower and more consistent during rumination than during eating; thus, the purpose of rumination is to improve feed digestion (Beauchemin 2018). Eating time differs from feeding time (FT) in that the latter represents meals and includes periods of inactivity, whereas eating time refers solely to the time spent prehending, chewing, and swallowing feed (Beauchemin 2018). Rumination is a key physiological function that provides the effective mechanical breakdown of roughage and thereby increases the substrate surface area to fermentative microbes (Moretti et al. 2018), but it also stimulates saliva production to help buffer the rumen and create a homeostatic environment for microbes (Beauchemin 2018). The rumen is a complex anaerobic microbial ecosystem, where various microorganisms, including bacteria, archaea, protozoa, fungi, and viruses interact and that, by fermentation, produce substances that are then absorbed into the rumen by the cow. Previous work on rumination has focused mainly on the effects of nutritional treatments (Jensen et al. 2016; Salfer et al. 2018) and digestion of forages (Jiang et al. 2017; Beauchemin 2018; Ben Meir et al. 2018). Schirmann et al. (2012) found that cows are most likely to ruminate about 4 h after periods of high dry matter intake (DMI) but they found no association between rumination behaviour and time of day. Beauchemin (2018) reported that the length of rumination bouts is not a good predictor of rumination time (RT) because many distractions can cause rumination to cease. Moreover, Salfer et al. (2018) found that daily rumination pattern is minimally influenced by diet. Jiang et al. (2017) reported that both eating time and RT increase with DMI, indicating that longer chewing time during eating does not fully reduce the need for additional mastication during rumination. Beauchemin (2018) concluded that there are complex interactions among dietary factors; thus, the correlation between RT and individual dietary factors was only low to moderate in these studies. For example, eating time and RT are affected by chemical and physical characteristics of the diet (Salfer et al. 2018), but other factors such as feeding management (access to feed), cow variability, and health can have equally large effects on both evaluated times (Beauchemin 2018). Although DMI is the primary driver of milk production (Aikman et al. 2008), RT may also be relatable to milk yield (MY) and milk composition (Byskov et al. 2015). Identification of the associations of cow feeding behaviour with productivity is important for supporting recommendations of strategies that optimize MY and composition (Johnson and DeVries 2018). In fact, some authors were already able to identify a positive association between MY and RT (e.g. Soriani et al. 2013; Byskov et al. 2015; Stone et al. 2017; Kaufman et al. 2018). However, most of the studies (e.g. Connor et al. 2013; Liboreiro et al. 2015; Kaufman et al. 2018) focused on the early stage of lactation, which is understandable because it has the highest effect on overall milk production.

The duration and frequency of lying behaviour and the time spent standing without eating appear to belong to the indicators of cow comfort that can affect performance and behaviour (Haley et al. 2000). The type of pen or stall, type of bedding, frequency of feed delivering and milking, management of hoof and leg diseases can have a substantial impact on feeding behaviour of dairy cows (Beauchemin 2018). Cows individually housed in large pens with mattress flooring were lying down 4.2 h/day longer than cows housed in tie-stalls on a concrete floor, while cows in tie-stalls stood without eating for longer (Haley et al. 2000). Krawczel et al. (2012) found that overcrowding and mixed parity pen decreased RT by 10% to 20% and 15%, respectively. Soriani et al. (2012) studied associations between RT, metabolic condition and health status. The same effect of heat stress and mastitis on RT was detected, i.e. 10% to 25% decrease of RT. Any deviation of RT from the baseline is a sign that rumen functions have been disrupted, and the MY potential of animal can be impeded. Rumination monitoring allows for earlier identification of health issues, can validate management strategies such as grouping, stocking density and heat stress abatement amongst others.

In the study of Van Hertem et al. (2014), hoof trimming and locomotion score affected activity time, resting time and MY of dairy cows. Each one-unit increase in locomotion score reduced the neck activity level by 4.488 bits/day (activity was measured according to how often the neck collar transmitted that the cow was moving) and trimming significantly reduced neck activity levels (380 ± 6 bits/day was the average activity one day after trimming compared with 389 ± 6 bits/day before trimming).

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The objective of this study was to determine associations of time spent for ruminating with MY in the early, mid and late stage of lactation. We hypothesized that greater RT would be associated with greater MY. We also assumed that the mean level of rumination time (MRT) would affect total MY produced during the whole lactation. The final objective of our study was to describe the feeding behaviour pattern in the early, mid and late stage of lactation.

MATERIAL AND METHODS

The data set observed in this study consisted of 2 777 dairy cows on nine commercial dairy farms during the years 2017 to 2019. The Holstein dairy cows involved in this study were raised in a free-stall barn located in three countries. Seven farms were situated in Ireland, one in Germany and one in Australia. The diet composition differed depending on the country, region, management of each commercial farm, and feeding company services used. All evaluated cows had unrestricted feed access. The dairy cows kept on farms in Ireland and Australia had a diet primarily made up of grass, which was either grazed or supplied as hay or silage, with a small amount of grain and mineral supplements to fill any nutritional gaps. Cows on the dairy farm in Germany were fed a TMR (a mixture of forage and grain) once daily *ad libitum*. The parity of the cows ranged from one to 12 (this range was split into three groups for analysis: first lactation, which included 1 023 cows; second lactation, which included 1 102 cows; ≥ third lactation, which included 1 980 cows) and all cows were monitored for daily milk yield and behaviour (RT, FT, resting and activity time). Milk yield and behaviour data were obtained from Milk Manager Software (Dairymaster, Co., Causeway, Ireland) at the end of the trial. Animals were not of the same age at the start of data collection, and therefore the lactation categories are unbalanced (i.e. the dataset contains older cows).

Both Salfer et al. (2018) and Niu et al. (2017) found that the daily pattern of feed intake appears to be influenced minimally by the source and concentration of fibre, starch, and fatty acids. The influence of diet was not considered in this study which analysed activity simply from a behavioural standpoint. Owing to the natural daily pattern of intake not being influenced by diet, the ruminal fermentation of cows ends up being inconsistent, especially if TMR high in concentrates are fed. Therefore it is worth noting that variation in diet may be a source of variation and a topic of future research.

Monitoring of MY

All participating farms milked 2 × daily and MY of each milking (Weighall Milk Meter, Dairymaster, Co., Causeway, Ireland) was recorded daily from four to 305 days in milk (DIM). Milk weights for the morning and afternoon milkings were summed to obtain daily MY; if data were missing at any milking due to technical problems, the MY for that day was reported as a missing value and were removed (n = 59 287). Each daily milking record contained the date of milking and a time-of-day indicator (AM or PM), MY (kg) and a cow identification number.

Monitoring of behaviour

The behaviour was measured using the behaviour-monitoring collar (MooMonitor+, Dairymaster, Co., Causeway, Ireland) of each animal 24 h/day. The MooMonitor+ recording system stores information every minute and then summarizes this data on an hourly basis. Dairymaster's MooMonitor+ is the first system validated in both indoor (Grinter et al. 2019) and outdoor (Werner et al. 2019) systems. Grinter et al. (2019) added that the behaviour-monitoring collar (MooMonitor+, Dairymaster, Co., Causeway, Ireland) performed precisely, with very high correlations for ruminating, feeding, and resting behaviours. The behaviour of dairy cows (RT, FT, resting and activity time) was summed to obtain total measured time per day; if the total time was less than 1 440 minutes due to technical problems, the behaviour measurement was reported as a missing value and was removed (n = 526 314). Table 1 provides descriptive statistics of evaluated behaviour and an ethogram of behaviour classification for visual observations.

Resting time includes lying and standing behaviour. A lying event was defined as any time the cow was lying with all four limbs on the ground. Lying events began when the posterior end contacted the ground and finished when the posterior end was off the ground. A standing activity was cat-

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Table 1. Evaluated parameters (dependent variables)

	n	Mean	SD	Minimum	Maximum
Milk yield (kg/day)	710 163	23.2	7.5	3.0	50.0
Lactations (*n*)	710 163	2.7	1.6	1	12
DIM (day)	710 163	153	81	4	305
RUT (min/day)	710 163	504	93	226	783
FT (min/day)	710 163	479	110	135	796
RET (min/day)	710 163	360	94	89	638
AT (min/day)	710 163	96	45	5	231

AT = activity time (any other activity such as drinking, walking, grooming, licking, rubbing, and interacting with other cows); DIM = days in milk; FT = feeding time [the cow with the muzzle in contact with feed, including sorting, smelling, and chewing feed (not stopping for ≥ 5 s)]; RET = resting time (includes lying and standing behaviour; a lying event was defined as any time the cow was lying with all four limbs on the ground; lying events began when the posterior end contacted the ground and finished when the posterior end was off the ground; a standing activity was categorized by the cow standing static for ≥ 5 s, with all four hooves on the ground); RUT = rumination time (regurgitation and remastication of a bolus with a rhythmic jaw movement; a break between bolus exchanges of ≥ 5 s was recorded as different activity)

egorized by the cow standing static for ≥ 5 s, with all four hooves on the ground.

Statistical analyses

Two analyses were conducted using 2 777 multiparous Holstein cows. Analysis 1 was conducted for cows in early (four to 100 DIM; 2 693 cows), mid (101 to 200 DIM; 2 632 cows), and late (201 to 305 DIM; 2 480 cows) lactation. Finally, 1 412 cows used in analysis 1 were also used in analysis 2.

Before analyses, all data were screened for normality and outliers using the UNIVARIATE procedure of SAS software v9.4 (SAS Institute Inc., Cary, NC, USA). Outliers (defined as those values > 1.5 times the interquartile range above the third quartile or below the first quartile) were detected for MY (n = 3 129), RT (n = 13 507), FT (n = 12 373), resting time (n = 16 793), activity time (n = 39 856), and thus they were excluded from the analyses. The total number of removed daily measures from calculation was 62 194, the mean values for which were: days in milk (DIM) 141 ± 86 days, MY 25.5 ± 14.0 kg, RT 400 ± 191 kg, FT 325 ± 188 kg, resting time 496 ± 297 kg and activity time 218 ± 129 kg. All daily measures that satisfied the criteria are shown in Table 1, in total 2 777 dairy cows and 710 163 daily milking records.

The violin plots (Figures 1 and 2) show a level of milk yield and behaviour on each evaluated farm. The advantage of the violin plot over the box plot is that the violin plot also shows the entire distribution of the data, and we can better imagine the conditions on the evaluated farms. Figure 3 shows aggregate values of RT and FT based on DIM of all evaluated cows (i.e. 'aggregate' denotes the mean value averaged across all evaluated cows for each DIM).

Analysis 1. To address our first objective, we individually associated RT with MY data in the three stages of lactation (early, mid and late) across all cows. The independent variables were RT, and MY groups (Tables 2 and 3). The stages of lactation were categorized by splitting the 305-day period

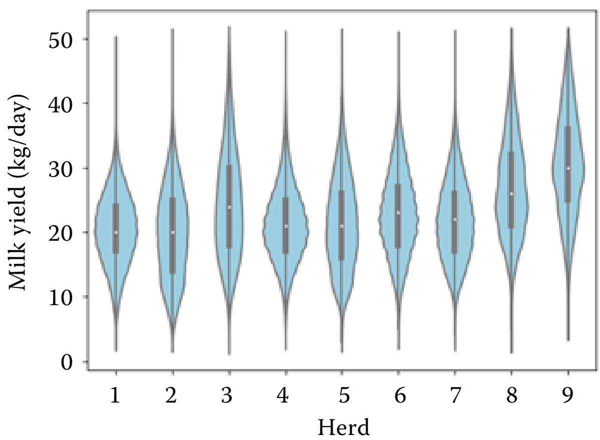

Figure 1. Violin plot of milk yield according to evaluated herds in the range of four to 305 days in milk and one to 12 lactations

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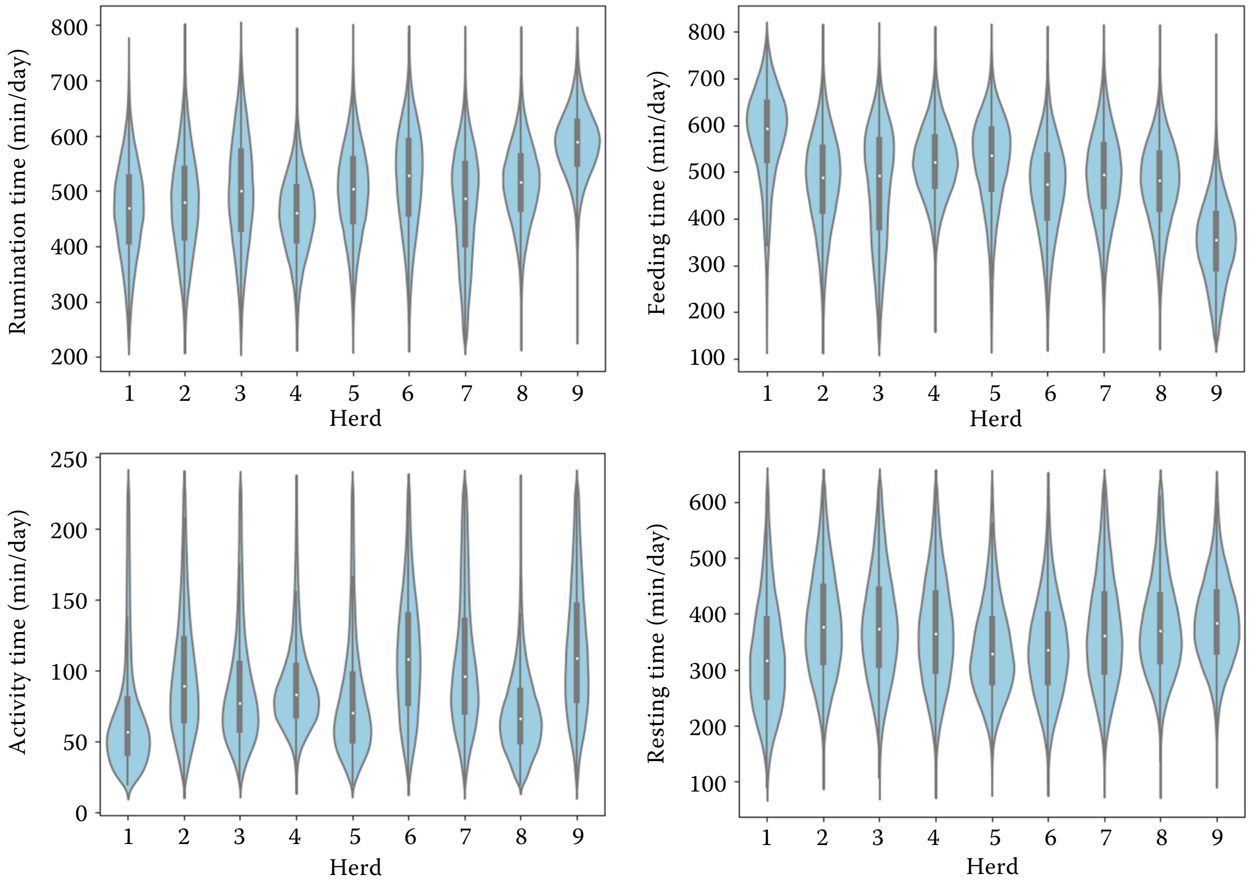

Figure 2. Violin plot of rumination, feeding, resting and activity time according to evaluated herds in the range of four to 305 days in milk and one to 12 lactations

into three hundred-day parts: four to 100 DIM (early), 101 to 200 DIM (mid) and 201 to 305 DIM (late). In terms of biological and economic parameters, we were particularly interested in a high RT above 600 min/day (Table 2). According to Watt et al. (2015), 600 min/day is the lowest level of the physiological maximum of RT. MY groups were categorized into high, mid and low production according to thresholds specific to each stage of lactation (Table 3). The most important group for evaluation of MY was the group with the highest production per lactation stage, i.e. ≥ 23 kg/day

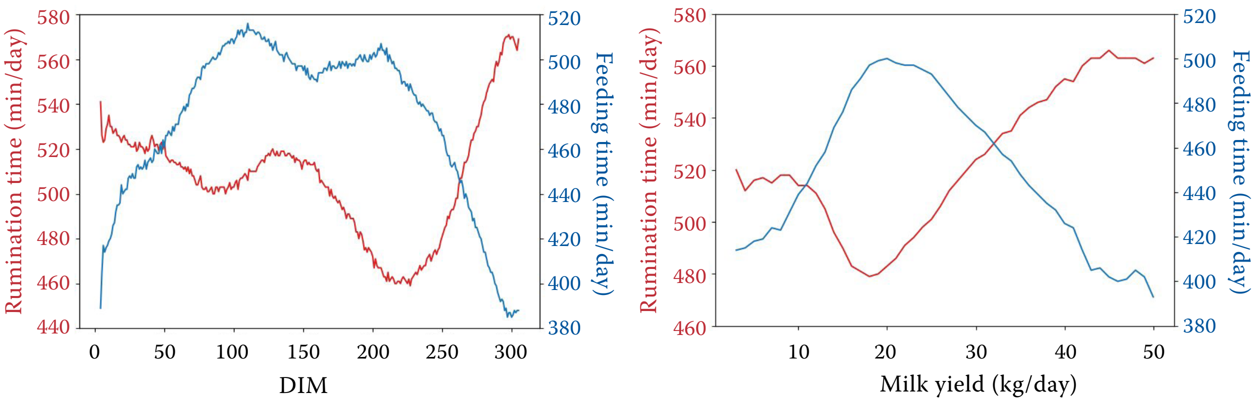

Figure 3. The aggregate values (n = 9 herds, 2 777 dairy cows, 710 163 daily records) of rumination and feeding time according to days in milk (DIM) and level of milk yield in the range of four to 305 DIM and one to 12 lactations DIM = 153 ± 81 days (mean ± SD), lactations = 2.7 ± 1.6 (mean ± SD)

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Table 2. Effects of rumination time on production and behaviour outcomes

Lactation phase (DIM)	Early (4 to 100)			Mid (101 to 200)			Late (201 to 305)		
Rumination time (min/day)	≥ 601	600 to 401	≤ 400	≥ 601	600 to 401	≤ 400	≥ 601	600 to 401	≤ 400
n (daily measures)	41 053	147 297	27 385	31 382	202 743	29 222	36 515	150 177	44 389
n (cows/herds)	2 239/9	2 675/9	2 272/9	2 173/9	2 622/9	2 113/9	2 095/9	2 457/9	2 069/9
Milk yield (kg/day)	29.5 ± 0.27^{a}	29.4 ± 0.27^{a}	28.9 ± 0.27^{b}	25.0 ± 0.23^{a}	25.0 ± 0.22^{a}	24.3 ± 0.23^{b}	17.7 ± 0.21^{c}	19.7 ± 0.21^{b}	20.4 ± 0.21^{a}
Feeding time (min/day)	386 ± 4.03^{c}	458 ± 3.95^{b}	520 ± 4.02^{a}	425 ± 3.34^{c}	486 ± 3.26^{b}	536 ± 3.35^{a}	366 ± 3.65^{c}	460 ± 3.57^{b}	532 ± 3.63^{a}
Resting time (min/day)	334 ± 3.57^{c}	371 ± 3.50^{b}	453 ± 3.56^{a}	307 ± 3.01^{c}	360 ± 2.93^{b}	444 ± 3.01^{a}	360 ± 3.24^{c}	392 ± 3.17^{b}	455 ± 3.23^{a}
Activity time (min/day)	86 ± 1.93^{c}	94 ± 1.90^{b}	106 ± 1.93^{a}	89 ± 1.71^{b}	91 ± 1.67^{b}	94 ± 1.71^{a}	78 ± 1.71^{c}	89 ± 1.68^{b}	95 ± 1.71^{a}
Feeding/resting ratio	1.36 ± 0.03^{b}	1.43 ± 0.03^{a}	1.28 ± 0.03^{c}	1.61 ± 0.03^{a}	1.50 ± 0.03^{b}	1.28 ± 0.03^{c}	1.15 ± 0.02^{c}	1.32 ± 0.02^{a}	1.27 ± 0.02^{b}
Feeding/activity ratio	6.25 ± 0.17^{b}	6.67 ± 0.17^{a}	6.62 ± 0.17^{a}	6.51 ± 0.16^{c}	7.21 ± 0.15^{b}	7.74 ± 0.16^{a}	6.53 ± 0.16^{c}	7.00 ± 0.16^{b}	7.59 ± 0.16^{a}
Resting/activity ratio	5.23 ± 0.12^{b}	5.30 ± 0.11^{b}	5.85 ± 0.12^{a}	4.50 ± 0.09^{c}	5.11 ± 0.09^{b}	6.18 ± 0.09^{a}	6.12 ± 0.13^{b}	5.90 ± 0.12^{c}	6.48 ± 0.13^{a}

DIM = days in milk

$^{a–c}$Within a row, mean values related to the same explanatory variable with different superscript letters are significantly different ($P < 0.05$)

Table 3. Effects of milk yield on behaviour outcomes

Lactation phase (DIM)	Early (4 to 100)			Mid (101 to 200)			Late (201 to 305)		
Milk yield (kg/day)	≥ 35	34.9 to 21	≤ 20.9	≥ 30	29.9 to 18	≤ 17.9	≥ 23	22.9 to 13	≤ 12.9
n (daily measures)	37 772	147 720	30 243	38 074	187 276	37 997	39 596	146 120	45 365
n (cows/herds)	1 594/9	2 635/9	1 841/9	1 581/9	2 576/9	1 857/9	1 777/9	2 406/9	1 893/9
Rumination time (min/day)	522 ± 3.54^{a}	517 ± 3.43^{b}	511 ± 3.57^{c}	507 ± 3.17^{a}	499 ± 3.07^{b}	487 ± 3.19^{c}	474 ± 3.57^{c}	493 ± 3.47^{b}	535 ± 3.57^{a}
Feeding time (min/day)	457 ± 4.69^{a}	449 ± 4.56^{b}	433 ± 4.73^{c}	496 ± 4.00^{a}	486 ± 3.88^{b}	476 ± 4.03^{c}	490 ± 4.37^{a}	462 ± 4.25^{b}	411 ± 4.36^{c}
Resting time (min/day)	366 ± 4.08^{c}	376 ± 3.96^{b}	400 ± 4.12^{a}	346 ± 3.68^{c}	362 ± 3.57^{b}	384 ± 3.71^{a}	389 ± 3.82^{c}	401 ± 3.72^{b}	415 ± 3.82^{a}
Activity time (min/day)	94 ± 2.12^{b}	96 ± 2.07^{a}	95 ± 2.14^{ab}	90 ± 1.97^{b}	93 ± 1.92^{a}	92 ± 1.99^{ab}	89 ± 1.90^{a}	85 ± 1.86^{b}	81 ± 1.90^{c}
Feeding/resting ratio	1.43 ± 0.03^{a}	1.38 ± 0.03^{b}	1.25 ± 0.03^{c}	1.60 ± 0.03^{a}	1.50 ± 0.03^{b}	1.37 ± 0.03^{c}	1.39 ± 0.02^{a}	1.29 ± 0.02^{b}	1.11 ± 0.02^{c}
Feeding/activity ratio	6.71 ± 0.18^{a}	6.49 ± 0.18^{b}	6.41 ± 0.18^{b}	7.31 ± 0.18	7.12 ± 0.17	7.13 ± 0.18	7.26 ± 0.18^{a}	7.27 ± 0.18^{a}	7.00 ± 0.18^{b}
Resting/activity ratio	5.27 ± 0.13^{b}	5.32 ± 0.12^{b}	5.70 ± 0.13^{a}	4.82 ± 0.11^{c}	5.01 ± 0.10^{b}	5.37 ± 0.11^{a}	5.73 ± 0.14^{c}	6.28 ± 0.14^{b}	6.89 ± 0.14^{a}
Rumination/feeding ratio	1.31 ± 0.02^{b}	1.32 ± 0.02^{b}	1.37 ± 0.02^{a}	1.12 ± 0.02	1.13 ± 0.02	1.14 ± 0.02	1.04 ± 0.02^{c}	1.18 ± 0.02^{b}	1.46 ± 0.02^{a}
Rumination/resting ratio	1.56 ± 0.03^{a}	1.52 ± 0.03^{b}	1.41 ± 0.03^{c}	1.61 ± 0.03^{a}	1.52 ± 0.03^{b}	1.38 ± 0.03^{c}	1.33 ± 0.02^{b}	1.34 ± 0.02^{b}	1.41 ± 0.02^{a}
Rumination/activity ratio	7.50 ± 0.18	7.33 ± 0.18	7.36 ± 0.18	7.16 ± 0.15^{a}	7.02 ± 0.15^{ab}	6.96 ± 0.15^{b}	6.90 ± 0.18^{c}	7.69 ± 0.17^{b}	8.71 ± 0.18^{a}
R and F mean (min/day)	490 ± 2.32^{a}	484 ± 2.26^{b}	472 ± 2.34^{c}	502 ± 2.09^{a}	493 ± 2.03^{b}	482 ± 2.11^{c}	481 ± 2.11^{a}	477 ± 2.07^{b}	472 ± 2.12^{c}

DIM = days in milk; R and F mean = mean of rumination and feeding time

$^{a–c}$Within a row, mean values related to the same explanatory variable with different superscript letters are significantly different ($P < 0.05$)

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in early lactation, > 30 kg/day in mid-lactation and ≥ 35 kg/day in late lactation (Table 3). The daily mean of all behaviours and ratios between RT, FT, resting and activity time (dependent variables) was calculated for better understanding of associations between dairy cows' behaviour and production (Tables 2 and 3).

The RT and MY groups were subjected to a repeatability model using the MIXED procedure of SAS software v9.4 (SAS Institute Inc., Cary, NC, USA) (i.e. applying a mixture of general linear models with fixed and random effects), treating lactation in the same animal as a repeated measure and cow within farm as a random effect. All considered effects were statistically significant ($P < 0.001$, Equation 1). Tukey's test was used to determine significant differences between means (Verbeke and Molenberghs 2000). The covariance structure was compound symmetry, selected by best fit according to Akaike and Schwarz Bayesian information criterion.

$$y_{ijklmno} = \mu + H_i + Y_j + S_k + P_l + B_m + Z_n + e_{ijklmno} \quad (1)$$

where:

$y_{ijklmno}$ – value of the dependent variable (listed in Tables 1–5);

μ – overall mean;

H_i – effect of the i^{th} herd (i = 1 to 9);

Y_j – effect of the j^{th} year of calving (j = 2017, 2018, 2019);

S_k – effect of the k^{th} season of the evaluated day (k = spring, summer, autumn, or winter);

P_l – effect of the l^{th} parity (l = 1 to 12, repeated effect);

B_m – effect of m^{th} RT, or MY class (Tables 2 and 3);

Z_n – effect of the n^{th} cow (n = cows within farm, random effect);

$e_{ijklmno}$ – random error.

Pearson correlation using the CORR procedure of SAS software v9.4 (SAS Institute Inc., Cary, NC, USA) was used to assess the relationship between

Table 4. Mean values for milk yield (MY, kg/day) according to evaluated herds in the range of four to 305 days in milk (DIM) and one to 12 lactations (L, *n*)

Herd No.	*n* (daily measures/cows)	MY (mean ± SD)	DIM (mean ± SD)	L (mean ± SD)
1	37 668/144	20.5 ± 5.6	123 ± 69	1.8 ± 0.9
2	57 137/206	19.8 ± 7.0	174 ± 77	3.1 ± 1.3
3	58 138/203	24.4 ± 8.5	145 ± 82	2.8 ± 1.6
4	86 166/345	21.3 ± 5.9	140 ± 82	2.5 ± 1.5
5	65 038/194	21.3 ± 7.1	159 ± 76	2.6 ± 1.5
6	201 076/936	22.9 ± 6.5	152 ± 83	3.2 ± 2.0
7	82 078/254	22.0 ± 6.4	162 ± 78	2.5 ± 1.5
8	56 529/164	26.9 ± 7.6	164 ± 75	2.9 ± 1.6
9	66 336/331	30.6 ± 8.0	152 ± 84	2.0 ± 0.7

Table 5. Mean values for rumination (RT, min/day), feeding (FT, min/day), resting (RET, min/day) and activity (AT, min/day) time according to evaluated herds in the range of four to 305 days in milk and one to 12 lactations

Herd No.	*n* (daily measures/cows)	RT (mean ± SD)	FT (mean ± SD)	RET (mean ± SD)	AT (mean ± SD)
1	37 668/144	466 ± 86	581 ± 102	325 ± 101	68 ± 43
2	57 137/206	478 ± 91	482 ± 102	383 ± 95	97 ± 45
3	58 138/203	501 ± 100	473 ± 124	379 ± 98	87 ± 41
4	86 166/345	458 ± 72	523 ± 78	370 ± 99	89 ± 33
5	65 038/194	500 ± 83	522 ± 100	339 ± 87	80 ± 42
6	201 076/936	522 ± 93	467 ± 99	341 ± 90	110 ± 48
7	82 078/254	474 ± 100	491 ± 98	369 ± 100	106 ± 48
8	56 529/164	514 ± 72	478 ± 91	379 ± 90	70 ± 31
9	66 336/331	586 ± 62	353 ± 89	388 ± 79	114 ± 47

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the behaviour of dairy cows and MY. Correlations on a daily basis were estimated across cows.

Analysis 2. The next objective was to determine how total MY varied according to MRT. The cows with individual milk production records during the first three lactations that lasted at least 100 days with at least one measurement during the first 30 DIM were included in the analyses (n = 1 412 cows, nine herds). The MRT of the dairy cows was divided into three evaluated groups in the first three lactations (Table 6 and Figure 4). We were especially interested in a high MRT above 550 min/day because we expected that those will be the high-yielding cows.

The MilkBot function (Ehrlich 2011) was used to fit milk production curves. The MilkBot predicts milk yields (Y) as a function of time after parturition. Four parameters: a (scale), b (ramp), c (offset), and d (decay) control the shape of the lactation curves. Euler's number e is the base of the natural logarithm, approximately 2.718, and m is the length of DIM (Ehrlich 2011). Details of the MilkBot model can be found here: http://dairysight.com/milkbot/model.

$$Y(m) = a\left(1 - \frac{e^{\frac{c-m}{b}}}{2}\right) e^{-dm} \quad (2)$$

Equation 2 was used to describe milk production curves for the first three lactations (Table 6 and Figure 4). MY data of each MRT group was fitted to the MilkBot model using an implementation of the Levenberg-Marquardt algorithm (Python v3.7.3., LMFIT package; Newville et al. 2016) to minimize the mean square error (MSE). Fitted parameter values and MSE for each aggregate curve are reported in Table 6. Figure 4 shows each aggregate curve plotted with the data points to which it was fitted. Final MSE values varied between 0.22 kg and 1.18 kg, depending mainly on the number of lactations in the group.

Mathematical manipulation of Equation 2 allows the calculation of peak day and MY, cumulative production for the first 100 days, whole lactation (305 days) and average daily MY (Ehrlich 2011).

Figures 1–4 were created with Python v3.7.3 (Matplotlib package; Hunter 2007).

RESULTS AND DISCUSSION

RT can be assessed in two ways, i.e. baseline or average RT (e.g. min/day) or deviation (Δ) from

Table 6. Calculated parameters of lactation curves according to the mean of rumination time (min/day) for the first three lactations using the MilkBot function (Ehrlich 2011)

Mean of rumination time	1. lactation ≥ 551	1. lactation 550 to 431	1. lactation ≤ 430	2. lactation ≥ 551	2. lactation 550 to 431	2. lactation ≤ 430	3. lactation ≥ 551	3. lactation 550 to 431	3. lactation ≤ 430
n (cows/herds)	23/4	327/9	64/6	114/7	436/9	44/7	78/6	431/9	45/6
Scale*	32.1 ± 0.42	27.9 ± 0.22	23.8 ± 0.29	44.8 ± 0.39	46.6 ± 3.17	31.7 ± 0.45	45.0 ± 0.15	40.4 ± 0.41	49.2 ± 4.17
Ramp*	29.4 ± 2.85	32.2 ± 1.96	27.3 ± 3.99	33.0 ± 2.00	100.0 ± 16.10	40.7 ± 2.88	15.1 ± 0.54	36.9 ± 2.28	100.0 ± 17.28
Offset*	−5.8 ± 1.54	−11.0 ± 1.12	−17.0 ± 3.64	−10.3 ± 1.04	−6.4 ± 6.11	−6.3 ± 0.94	−0.6 ± 0.36	−10.7 ± 0.99	10.8 ± 7.97
Decay*	0.002 ± 6.25×10^{-5}	0.002 ± 3.83×10^{-5}	0.002 ± 5.90×10^{-5}	0.003 ± 4.21×10^{-5}	0.004 ± 2.01×10^{-4}	0.003 ± 6.43×10^{-5}	0.003 ± 1.99×10^{-5}	0.003 ± 4.82×10^{-5}	0.004 ± 2.51×10^{-4}
Mean squared error (kg)	1.18	0.22	0.65	0.53	0.41	0.40	0.32	0.39	0.68
Peak day	58.8	57.0	51.0	46.3	49.6	55.8	36.3	48.8	66.8
Peak MY (kg)	27.0	23.4	20.4	35.5	27.3	23.9	38.6	31.4	26.9
MY 1st 100 days of DIM (kg)	2 553	2 240	1 955	3 395	2 664	2 277	3 575	3 013	2 580
MY 305 days of DIM (kg)	6 963	6 070	5 228	8 459	6 671	5 842	8 679	7 570	6 738
Average daily MY (kg/day)	22.8	20.0	17.1	27.7	21.9	19.2	28.5	24.8	22.1

DIM = days in milk; MY = milk yield; *the MilkBot function (Ehrlich 2011) predicts milk yields (Y) based on four calculated parameters: scale, ramp, offset, and decay

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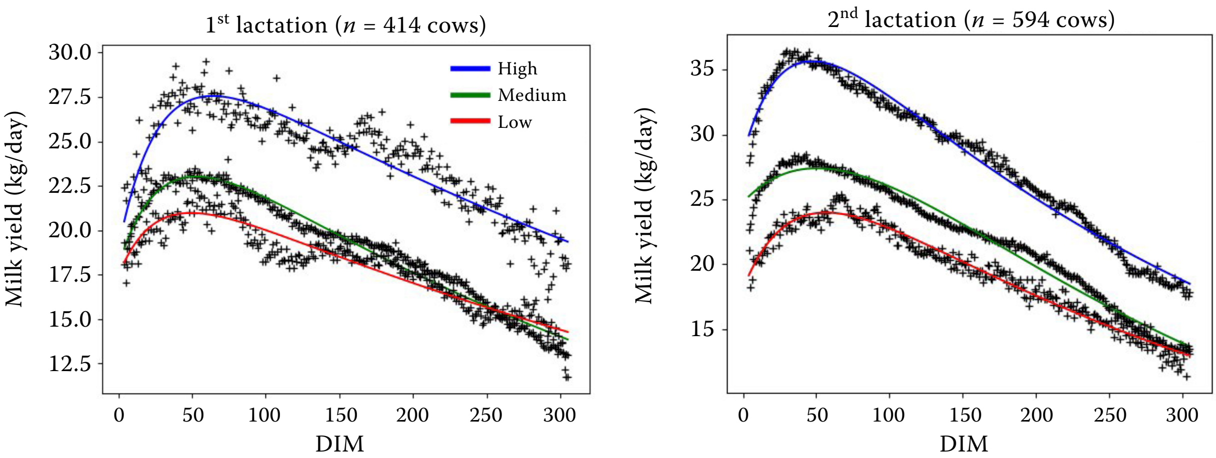

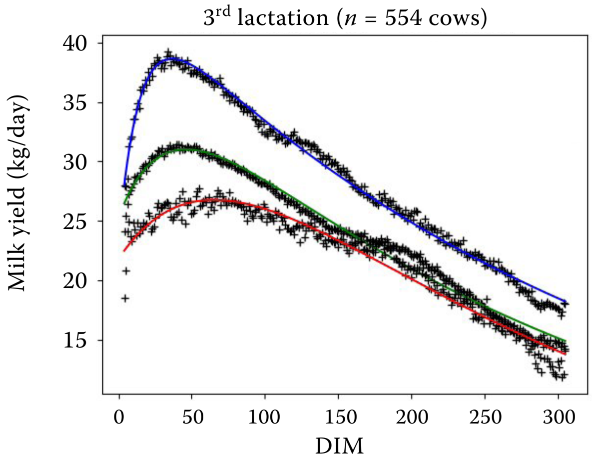

Figure 4. The lactation curves according to the mean of rumination time for the first three lactations using the MilkBot function (Ehrlich 2011)

Means of rumination time were grouped as high (≥ 551 min/day; 1st lactation: n = 4 478, 574 ± 25 min/day; 2nd lactation: n = 23 862, 585 ± 28 min/day; 3rd lactation: n = 17 440, 589 ± 30 min/day), medium (550 to 431 min/day; 1st lactation: n = 71 821, 488 ± 30 min/day; 2nd lactation: n = 96 020, 496 ± 30 min/day; 3rd lactation: n = 96 222, 496 ± 30 min/day), and low (≤ 430 min/day; 1st lactation: n = 13 563, 409 ± 15 min/day; 2nd lactation: n = 8 320, 409 ± 19 min/day; 3rd lactation: n = 8 908, 414 ± 19 min/day); data are presented as n (daily measures), mean ± SD (min/day)

baseline RT. In the present study, we focused on average RT (min/day) and aggregate values of RT (min/day) to find an association between RT (min/day) and MY (kg/day) during lactation.

Descriptive results

Table 1 provides an overview of the descriptive results of the examined traits. Figure 1 and 2 and Tables 4 and 5 show the level of the examined traits for each evaluated herd in our study. Herds 1 and 2 had the lowest average MY, i.e. 20.5 ± 5.6 kg/day and 19.8 ± 7.0 kg/day, respectively (Figure 1); whereas herds 8 and 9 achieved the highest average MY, i.e. 26.9 ± 7.6 kg/day and 30.6 ± 8.0 kg/day, respectively (Figure 1). The highest-yielding herd 9 was in the group of the highest average RT ≥ 514 min/day together with herd 6 and 8 (Figure 2) and also achieved the lowest level of average FT 353 ± 89 min/day and the highest level of resting and activity time, i.e. 388 ± 79 min/day and 114 ± 47 kg/day, respectively (Figure 2).

Variability of rumination

Many recent studies laid the foundation for our understanding of the mechanics of rumination, the physiological role of rumination for the cow, and how RT is affected by changes in chemical composition and physical characteristics of the diet (e.g. Beauchemin 2018; Ben Meir et al. 2018; Salfer et al. 2018) as well as the types of diets fed, and the production systems used (e.g. Dann et al. 2015; Watt et al. 2015; Jiang et al. 2017). In our study, we assessed how the RT is changing during lactation and how different levels of RT affect milk production and other behaviours (FT, resting and activity time). In summarizing the literature for dairy cows, White et al. (2017) reported that mean RT was 436 min/day (n = 179), ranging from 236 to 610 min/day, and Zebeli et al. (2006) reported that mean RT was 434 min/day (n = 99), ranging from 151 to 630 min/day and finally Beauchemin (2018) presented that mean RT in reviewed literature was about 420 min/day, ranging from 150 to 630 min/day. Our study showed

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that mean RT was 504 min/day (n = 710 163), ranging from 226 to 783 min/day (Table 1). The large variability in mean RT occurs for many reasons, including the measurement technique accuracy (which may be influenced by the sensitivity of the neck-mounted device to bolus exchange and the ability of the algorithm to distinguish that activity from other activities), variability between animals and the physical and chemical composition of the diet (Beauchemin 2018). Variability occurs also between breeds. Holsteins spent more time ruminating per day compared with Jerseys, but Jerseys spent more time ruminating per unit of ingested feed (Aikman et al. 2008). Some studies also reported higher RT in multiparous compared with primiparous cows, but this difference appears to be due to differences in DMI as RT adjusted for the intake of primiparous cows is usually lower than or similar to that of multiparous cows (Dado and Allen 1994; Beauchemin 2018). Beauchemin (2018) added that primiparous cows need to develop the full digestion system capacity during the first parity and thus RT is lower. Our study confirmed these findings, the multiparous cows ruminated longer than primiparous cows and the difference was 28 min/day (early lactation), 13 min/day (mid-lactation), 6 min/day (late lactation) and 15 min/day for the whole lactation (Table 7). The coefficient of variation for RT (min/day) among animals was reported as 16% (12 cows monitored, Dado and Allen 1994) and in another study 48% (79 cows monitored, Byskov et al. 2015). In the present study, the coefficient of variation for RT (min/day) was 18.5% (2 777 cows monitored) for the whole lactation period (Table 7). Watt et al. (2015) found that the physiological maximum RT was about 600 to 720 min/day, which may occur in cattle fed high-fibre diets and they added that most lactating dairy cows fed mixed diets seldom ruminate so long. In our study, only cows on farm 9 were fed TMR all the year round, which corresponded with the highest recorded MRT of 586 min/day (n = 66 336, farm 9; Figure 2). Optimum RT is needed to minimize the risk of rumen acidosis, enhance fibre digestion, and promote high levels of feed intake in dairy cows (Beauchemin 2018). Dairy cows mostly ruminate at night, but cattle also ruminate throughout the day when not interrupted by feeding and milking (Dado and Allen 1994; Paudyal et al. 2016).

Table 7. Correlations between four monitored behaviour variables using precision dairy farming technologies on 4 103 Holstein cows from four to 305 days in milk (DIM)*

Lactation phase (DIM)	Early (4 to 100)	Mid (101 to 200)	Late (201 to 305)	Whole (4 to 305)
n (daily measures/cows/herds)	215 735/2 693/9	263 347/2 632/9	231 081/2 480/9	710 163/2 777/9
Milk yield (kg/day)/rumination time (min/day)**	0.24	0.25	−0.06	0.16
Milk yield (kg/day)/feeding time (min/day)**	−0.18	−0.22	0.04	−0.10
Milk yield (kg/day)/resting time (min/day)**	−0.04	−0.00 (P = 0.15)	−0.02	−0.11
Milk yield (kg/day)/activity time (min/day)**	0.02	0.03	0.09	0.06
Rumination time (min/day)/feeding time (min/day**)	−0.55	−0.46	−0.58	−0.51
Rumination time (min/day)/resting time (min/day**)	−0.31	−0.41	−0.37	−0.36
Rumination time (min/day)/activity time (min/day**)	−0.08	0.02	−0.07	−0.04
Mean rumination time (primiparous/multiparous) (min/day)	492 ± 95/520 ± 94	495 ± 83/508 ± 83	489 ± 99/495 ± 102	492 ± 92/507 ± 94
Coefficient of variation (rumination time/feeding time, %)	18.5/24.3	16.6/20.4	20.5/23.8	18.5/23.0

*The Weighall Milk Meter (Dairymaster, Co., Causeway, Ireland) system provided daily milk weights per cow. The behaviour (rumination, feeding, resting and activity time) was measured using the behaviour-monitoring collar (MooMonitor+, Dairymaster, Co., Causeway, Ireland) of each animal 24 h/day
**All Pearson correlation coefficients across cows had statistical significance $P < 0.001$

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Complementarity between FT and RT

Beauchemin (2018) presented that lactating dairy cows spent about 4.5 h/day eating (range: 2.4–8.5 h/day) and 7 h/day ruminating (range: 2.5–10.5 h/day). Zebeli et al. (2006) and Jensen et al. (2016) reported that the maximum total chewing time was 16 h/day. We found that lactating dairy cows (during days in milk four to 305) spent about 8.0 h/day feeding (range: 2.3–13.0 h/day), 8.4 h/day ruminating (range: 3.8–13.1 h/day) and the total chewing time was not observed (Table 1). Dado and Allen (1994) found that the cow variability, determined by the coefficient of variation, for eating time (min/day) was about 17% and for FT (min/day) it was 2 to 3-times higher. In the present study, the coefficient of variation for FT (min/day) was 23.0% (2 777 cows monitored) for the whole lactation period (Table 7). Dado and Allen (1994) stated that for dairy cows with unrestricted feed access the correlation coefficient between eating time and RT was −0.62, indicating that cows that spend less time eating tend to ruminate longer. Ben Meir et al. (2018) found a negative relationship between average daily RT and FT ($r = -0.34$, $P = 0.03$), but no relation between daily RT and DMI ($r = 0.11$; $P = 0.48$). Dado and Allen (1994) added that there can be a compensatory relationship between eating time and RT. We found similar results in our study, the correlation coefficient between FT and RT was −0.51 ($P < 0.001$) for the whole lactation period (Table 7). A detailed relationship between FT and RT is displayed in Figure 3. A similar inverse relationship was reported also for cows with decreased eating time due to feed restriction or diet composition; RT increased to compensate for the longer particle size of swallowed feed due to feed restriction (Beauchemin 2018). Zebeli et al. (2006) and Jensen et al. (2016) reported that total chewing time is less variable than eating or RT. White et al. (2017) concluded that no such compensatory effect occurs if cows are ruminating near their physiological maximum, which is sometimes the case for high-yielding dairy cows. Our study found that high-yielding dairy cows in early (≥ 23 kg/day) and mid (≥ 30 kg/day) lactation achieved the highest RT [522 ± 3.54 min/day ($P < 0.05$) and 507 ± 3.17 min/day ($P < 0.05$)] and highest FT [457 ± 4.69 min/day ($P < 0.05$) and 496 ± 4.00 min/day ($P < 0.05$)], respectively (Table 3). As can be verified in Figure 3, the longest rumination times occur at the end of lactation, in a period when the average MY of the herd is significantly declining ahead of the dry-off period. While the average MY is significantly lower at this time, Table 3 shows that MY does not drop so much in cows that ruminate less. RT and FT were negatively correlated across the lactations (Table 7), however, in late lactation, RT increased compared to FT (Figure 3). This flip in the complementarity of RT and FT in late lactation is not well documented. One possible explanation is that the dry matter digestibility of grass starts to decline later in the grazing season, so the method of digestion may change to suit the diet. The stage of pregnancy may also affect digestion. The relationship is loosely linked to milk yield and further discussion on that is provided in the next section. This variability on whether cows have to spend more time ruminating to further breakdown their diet or not is probably the reason why the correlation between eating and rumination time for dairy cows was relatively low when examined across studies ($r = 0.27$, $P < 0.05$; White et al. 2017). Moreover, the RT and FT were the highest in the high MY groups, and the rumination/feeding ratio was the highest in the low MY groups in all lactation phases (Table 3). These findings showed that RT should not exceed a certain level of FT for maintaining the high milk yield performance. Further research is needed to find the range of the optimal ratio for each phase of lactation.

MY and RT

High-yielding cows tend to have greater feed intakes to support energy demand (Beauchemin 2018; Ben Meir et al. 2018), eat larger meals in less time, ruminate longer and drink more water compared to lower-producing cows (DeVries et al. 2004). Moreover, milk production can be affected by breed, lactation stage, age, nutrition, and management strategies (NRC 2001). A positive correlation between MY and RT was reported in early lactation cows (Liboreiro et al. 2015; Kaufman et al. 2018). Soriani et al. (2013) observed a positive correlation between RT and MY in mid-lactation cows. Our study can confirm these results, RT was positively associated with MY (Table 7) in early ($r = 0.24$, $P < 0.001$) and mid lactation ($r = 0.25$, $P < 0.001$). However, the correlation in late lacta-

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tion (r = –0.06, P < 0.001) diminishes and the direction changes. This can be explained by the fact that in late lactation, it is also later in the grazing season when the dry matter digestibility of grass starts to decline, so cows who spend more time ruminating do not benefit as much as cows who spend that time eating more grass. There may be more interesting findings to uncover here around the type of diet, parity and genetics, for example, high-yielding cows may require more energy at this time to regain the body condition and support the calf development.

Stone et al. (2017) reported a similar relationship between RT and MY (n = 36 cows, r = 0.30, P < 0.01). Kaufman et al. (2018) revealed that daily MY of cows in early lactation was moderately correlated with RT (r = 0.37 to 0.69 depending on parity and DIM). The positive association between RT and MY is indirectly related to DMI and composition of the diet (Beauchemin 2018). Schirmann et al. (2012) and Clement et al. (2014) reported that RT and DMI were not correlated across cows, and thus they concluded that main drivers of RT were chemical and physical characteristics of the diet. Meta-analysis across studies showed a low correlation (r ≤ 0.12) between eating time and dietary NDF content or forage NDF (FNDF) content because fibre content does not account for differences in intake (White et al. 2017). In the large study of De Mol et al. (2016) it was found that the correlation between eating time and feed intake was 0.53 in a TMR system and 0.56 in a partial TMR system. Beauchemin (2018) presented that the frequency of meals and overall meal duration are unique for individual cows, whereas eating rate and meal size are consistent among cows. Crossley et al. (2017) found that cows can modify their feeding behaviour to consume feed in a shorter period when necessary. Moreover, Ben Meir et al. (2018) revealed that high-yielding cows vastly differ in their feed efficiency. An example can be found in a study of Halachmi et al. (2016), where lactating cows produced similar yield (45 kg milk/day) but consumed varying amounts of DM (25 to 35 kg) from the same TMR at the same stage of lactation. In a study by Connor et al. 2013, feed efficiency showed heritability estimates from 0.20 to 0.36. Our study showed that FT decreased (~ 393 min/day) and RT increased (~ 566 min/day) from the level of MY 20 kg/day to reach the MY higher than 45 kg/day (Figure 3). High-yielding cows consume the same or higher amount of feed in a shorter period and/or they have better feed efficiency (Figure 3). Dado and Allen (1994) added that older cows eat faster than younger cows. DeVries et al. (2004) reported that subordinate cows and younger cows can be affected by increased competition, and it can affect their productivity. The opportunity for high-yielding dairy cows to eat whenever they want is important, especially in the period of increased feeding time during the early and mid-period of lactation (Figure 3). Finally, DeVries et al. (2004) concluded that increased feeding frequency might yield more stable and consistent ruminal fermentation and optimal patterns of RT. The highest MY during the whole lactation period was achieved by cows in the highest MRT group (≥ 551 min/day, Figure 4). We can confirm our hypothesis that the mean level of rumination time was correlated with the total MY produced over the whole lactation.

RT as a reflection of body condition

Rumination is a key part of the time budget between ruminating, eating, and resting, i.e. the ratio between these activities is influenced by the time each cow naturally takes or is allowed to ruminate. These variables are often reciprocal (Stone et al. 2017). In our study, RT was negatively correlated with resting time (r = –0.36, P < 0.001) and no correlation was found with activity time (r = –0.04, P < 0.001) in the whole lactation period (Table 7). Stone et al. (2017) reported a negative correlation between RT and lying time (r = –0.14), whereas a positive correlation was found to exist between RT and neck activity (r = 0.18). Moreover, lying time was negatively correlated with MY (r = –0.25). We found a negative correlation between MY and resting time (r = –0.11, P < 0.001) across the whole lactation period (Table 7). The highest feeding/activity ratio, ruminating/activity ratio, feeding/resting ratio and ruminating/resting ratio occurred in the highest MY group in the early and mid phases of lactation (Table 3). These results are likely to have two main causes. High-yielding cows produce milk close to the physiological maximum and are more susceptible to disruption of homeostasis due to various environmental stressors. It means they are less resilient to changes in their environment which can cause several illnesses and prolonged resting time and disrupt MY.

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Another reason can be that high-yielding cows' daily FT and RT are much higher, and there is no time for other activity. According to Stone et al. (2017) the neck activity would likely increase due to more frequent visits to the feed bunk by high-yielding cows. As noted by Krpalkova et al. (2016), animals have certain biological limits and any disruption of homeostasis in their bodies leads to difficulties in their future performance. According to Beauchemin (2018) the process of rumination plays a vital role; cows can voluntarily control their rumination and stop ruminating when disturbed or experiencing some discomfort (e.g. illness or pain). Several studies reported that RT deviated from the baseline due to lameness (Paudyal et al. 2016), mastitis (Schirmann et al. 2016), metritis (Liboreiro et al. 2015) and even oestrus or changes in milking or feeding frequency (Johnson and DeVries 2018). RT could also be associated with depressed rumen pH (DeVries et al. 2004). Our study also showed that resting/activity ratio and resting time were the highest in low-yielding groups ($P < 0.05$, Table 3). Lying is a high priority behaviour in dairy cattle in terms of health (Schirmann et al. 2012). Stone et al. (2017) added that cows with greater MY have higher nutrient requirements and may spend more time on feed consumption and rumination. Krpalkova et al. (2016) reported that some herds with high overall culling rate due to several illnesses had high milk yield performance. It means that the high-yielding cow may have a high milk yield and be profitable, but at the same time, the cow must maintain the healthy body condition. Cases of illness were shown to be correlated with increased resting time (animals are less active when they are ill). Therefore, an increase in resting time detected by cow wearable technology may be used as an early indicator of illness.

CONCLUSION

RT was found to be positively associated with MY in early and mid-lactation dairy cows across all parities. The MRT affected total MY produced during the whole lactation. Further, RT was found to be negatively associated with FT. This provides evidence to support the theory that complementarity between RT and FT exists. Moreover, for maintaining high performance, RT should not exceed a certain level of FT. However, further research is needed to determine and validate how this level changes over lactation. FT was higher than RT for MY up to 20 kg/day and then the sign of the ratio changed to reach higher MY. From this we conclude that high-yielding cows can have better feed efficiency and/or they have faster feed intake. This is in agreement with previous research, however previous research did not study the late lactation period. Our study presents interesting findings about the relationship between RT, FT and MY in late lactation. RT was found to be negatively correlated with both FT and MY in late lactation (note that overall average MY is lower in late lactation, but it does not decrease so much in cows who ruminate less). The paper proposes a number of reasons for the observed relationships including physiological, behavioural and diet-based ones. More research is needed to further investigate the effect of diet, housing conditions, stage of pregnancy and breeding on these relationships.

Conflict of interest

The authors declare no conflict of interest.

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