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System specification and validation of a noseband pressure sensor for measurement of ruminating and eating behavior in stable-fed cows

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ABSTRACT

Rumination and eating behavior are important indicators for assessing health and well-being in cattle. The objective of this study was to develop and validate a novel scientific monitoring device for automated measurement of ruminating and eating behavior in stable-fed cows to provide research with a measuring instrument for automated health and activity monitoring. The RumiWatch noseband sensor (Itin+Hoch GmbH, Liestal, Switzerland) incorporates a noseband pressure sensor, a data logger with online data analysis, and software. Automated measurements of behavioral parameters are based on generic algorithms without animal-specific learning data. Thereby, the system records and classifies the duration of chewing activities and enables users to quantify individual ruminating and eating jaw movements performed by the animal. During the course of the development, two releases of the system-specific software RumiWatch Converter (RWC) were created and taken into account for the validation study. The results generated by the two software versions, RWC V0.7.2.0 and RWC V0.7.3.2, were compared with direct behavioral observations. Direct observations of cow behavior were conducted on 14 Swiss dairy farms with an observation time of 1 h per animal, resulting in a total sample of 60 dairy cows. Agreement of sensor measurement and direct observation was expressed as Spearman correlation coefficients (r_s) for the pooled sample. For consolidated classification of sensor data (1-h resolution), correlations for rumination time were $r_s = 0.91$ (RWC V0.7.2.0) and $r_s = 0.96$ (RWC 0.7.3.2), and for eating time $r_s = 0.86$ (RWC 0.7.2.0) and $r_s = 0.96$ (RWC V0.7.3.2). Both software versions provide a high standard of validity and measuring performance for ruminating and eating behavior. The high to very high correlations between direct observation and sensor data demonstrate that the RumiWatch noseband sensor was successfully developed and validated as a scientific monitoring device for automated measurement of ruminating and eating activity in stable-fed dairy cows.

1. Introduction

Research in the field of Precision Livestock Farming has put a major effort on development and evaluation of technologies allowing early recognition of pathological and management-relevant behavioral changes and assessment of the individual health state in dairy cows (cf. review by Rutten et al., 2013). Hence, sensor devices for automated detection of health impairments in livestock are increasingly available and can provide effective management support in various types of farming systems. In dairy cattle nutrition, chewing activity has been identified as an important parameter to assess the adequate composition of a diet and the risk of ruminal acidosis (Yang and Beauchemin, 2007). Furthermore, ruminating activity may provide meaningful information on calving time and subclinical diseases or health disorders (Goff and Horst, 1997; Soriani et al., 2012). Accordingly, continuous measurements of cow feeding variables enable us to develop a more complete understanding of the dietary effects on digestive function and performance (Dado and Allen, 1993). The timeline and intensity of feeding activity provide information on the diurnal pattern of the behavior of ruminants, and identification of deviations may be used for detection of health impairments (Weary et al., 2009; Braun et al., 2014). Direct observation for measurement of ruminating and eating behavior is labor intensive, error-prone and hardly applicable for continuous observations on several animals simultaneously (Penning, 1983). For these reasons, several methods have been developed for automated, non-invasive measurement of chewing activity in ruminants. The working principle of

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these devices is mainly based on detection of jaw movements via strain or pressure sensors fitted to a halter (Luginbuhl et al., 1987; Matsui and Okubo, 1991; Dado and Allen, 1993). The best known approach is the IGER Behaviour Recorder (Penning, 1983; Penning et al., 1984; Rutter et al., 1997; Rutter, 2000). However, continuous recording is hereby limited to approximately 24 h and Nydegger et al. (2010) reported frequent damages of the IGER Behaviour Recorder when applied in loose housing systems, as the recorder's dimensions impeded the animals, particularly on entering and leaving the feed rack. Therefore, Nydegger et al. (2010) developed a compact-built pressure sensor system integrated into a halter (ART-MSR Jaw Movement Sensor, MSR Electronics GmbH, Seuzach, Switzerland), which allowed individual jaw movements to be recorded but required animal-specific learning data. The necessity of creating learning datasets for classification of the activities before starting the measurement is laborious, and recording time of this device was limited to a maximum of 40 h due to storage capacity and power supply (Nydegger et al., 2012). Meanwhile, technological progress in electronics led to increased battery lifetime, storage capacity, continuous recording time, and accuracy of automated measurements. Considering both scientific and commercial requirements for detailed analysis of the behavior and activity of ruminants, automated measurement technologies should generate information on the duration, intensity and diurnal pattern of chewing activities. Furthermore, a suitable method for automated recording of jaw movements needs to allow classification and quantification of individual jaw movements for a long operating time (i.e., weeks to several months) at a high resolution and with satisfactory measuring performance. The aim of this study was to develop and validate a novel scientific monitoring device for automated health and activity monitoring in dairy cows. The presented RumiWatch noseband sensor was developed by Agroscope Institute for Sustainability Sciences (Ettenhausen, Switzerland) in collaboration with Itin+Hoch GmbH and InnoClever GmbH (both Liestal, Switzerland) and enables automated measurements of ruminating, eating, and drinking behavior. Our aim in this paper was twofold. Firstly, to provide a complete and detailed technical specification of the functionality of this device and, secondly, to perform a validation focusing on the system's ability to quantify the duration of chewing activity and the number of jaw movements during rumination and eating. As the algorithms have undergone successive development, two releases of the device-specific software for behavior classification are currently available that allow repeated analysis of previously recorded noseband sensor data. Hence, a further aim of this study was to validate these two commercially available versions of the software applied to the same data set recorded by the RumiWatch noseband sensor in comparison with direct observation under field conditions in stable-fed cows.

2. Materials and methods

2.1. RumiWatch noseband sensor

The RumiWatch noseband sensor (Nydegger and Bollhalder, 2010, Swiss Patent CH 700 494 B1, Agroscope, Ettenhausen, Switzerland; manufactured and distributed by Itin+Hoch GmbH, Liestal, Switzerland) is a non-invasive sensor-based system enabling automated measurement of rumination, eating, drinking, movement and posture of the head in cattle. It comprises a noseband sensor, a data logger with online data analysis, and evaluation software. The noseband sensor consists of a glycol-filled silicone pressure tube with a built-in pressure sensor placed in the casing of a fully adjustable polyethylene halter over the bridge of the cow's nose (Fig. 1). Adjustable straps provide a proper fit of

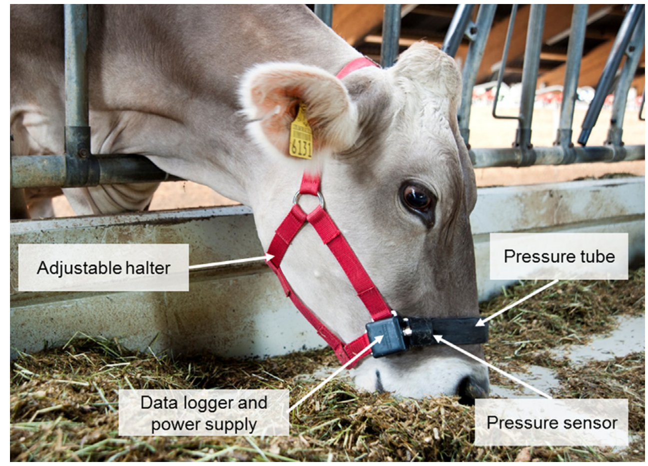

Fig. 1. Technical components of the RumiWatch noseband sensor.

the padded halters to the dimensions of the animal's head, in order to ensure wearing comfort, correct positioning of the sensor unit, and collection of valid data. The total weight of the noseband sensor including all components is approximately 700 g.

The pressure sensor is connected to a data logger placed in a protective casing on the right side of the halter. A second, identically constructed casing on the left side of the halter stores two 3.6-V lithium-ion batteries (Tadiran SL-761, Tadiran Batteries Ltd., Kiryat Ekron, Israel) for power supply of the electronic components. The data logger registers the pressure changes in the noseband sensor, triaxial accelerations of the halter, and ambient temperature at a constant logging rate of 10 Hz and saves the raw data as a binary file to a specific microSD memory card (Swissbit AG, Bronschhofen, Switzerland). Online data analysis with preliminary classification of measurement data is conducted via the device firmware that is operated by the onboard 16-bit CPU (MSP430, Texas Instruments Inc., Dallas, Texas, USA). During chewing activity, the curvature of the noseband is altered by the cow's jaw movement, exerting a pressure change in the pressure tube. Thus, the pressure sensor allows individual jaw movements to be recorded. Automatic classification and quantification of chewing activity is based on the logging of individual pressure peaks, whereby every peak above a detection threshold of 28 mbar is counted as a chew. Absolute peak height is not considered for classification of chewing activity, as the pressure head inside the silicone tube is not standardized. In consequence, chewing activity is classified according to the frequency of peaks, as characteristic peak rates and peak intervals during rumination, eating, drinking, and other activity (e.g., idling) allow distinguishing between jaw movements of these behaviors. Peak frequencies recorded by the noseband sensor during measurement of ruminating, eating, and drinking behavior are shown in Fig. 2a–c. The diagrams show that rumination is clearly distinguishable from eating activity. Homogeneous phases of jaw movements interrupted by bolus regurgitation cause the significant peak profile of ruminating activity. Peak rates during eating are more heterogeneous with irregular interruptions and altering peak frequencies due to the animal's partly increased bite rate and feed selecting behavior. A specific peak profile during drinking activity recorded by the noseband sensor is clearly distinguishable from those of rumination and eating (Fig. 2a–c). The shown diagrams represent typical measures that are obtained from noseband sensor recordings under normal operating conditions.

The raw data files of noseband sensor recordings contain all information logged at 10 Hz, comprising the date and time of mea-

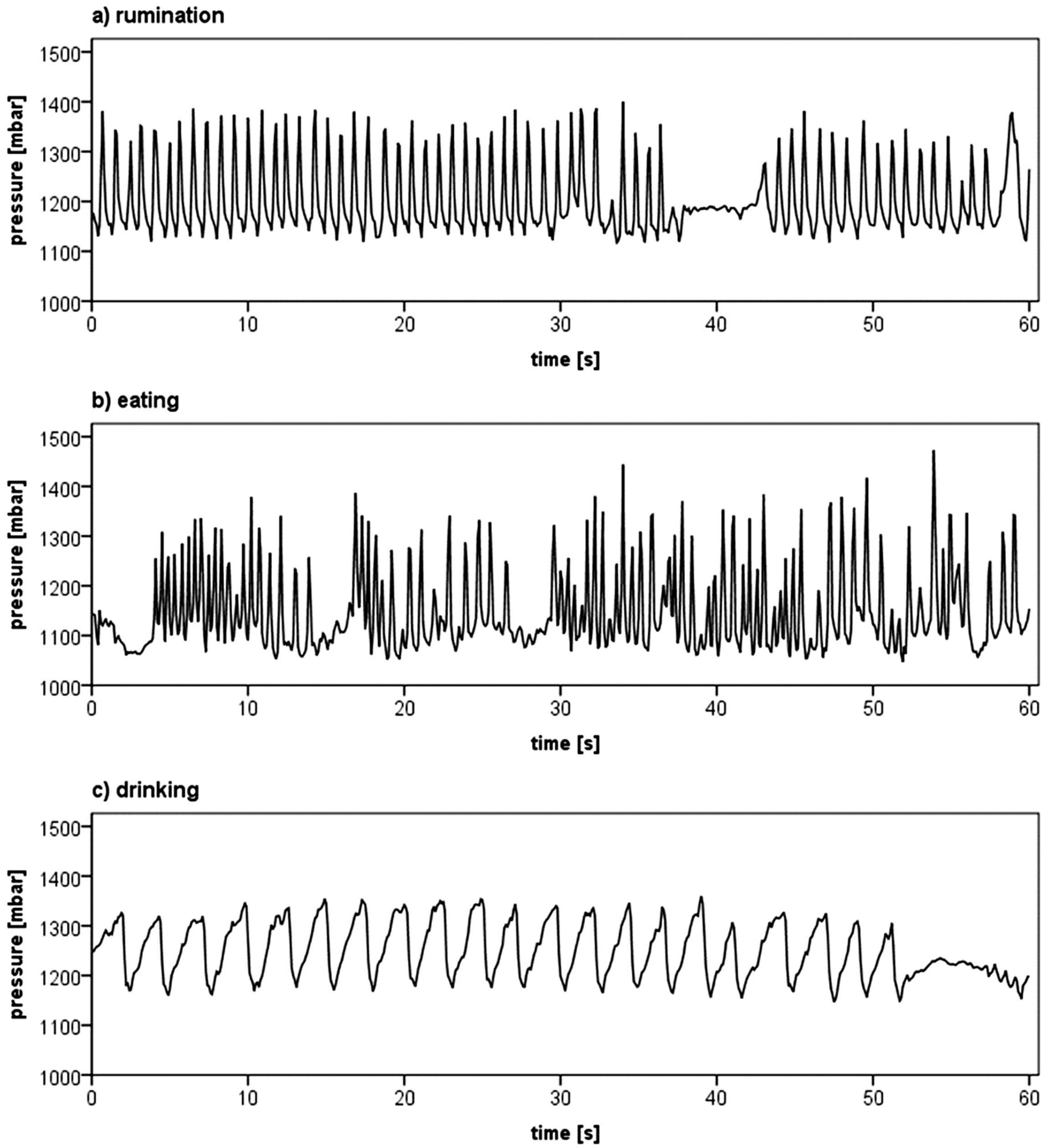

Fig. 2. (a–c) Peak profiles over a period of 60 s during (a) rumination, (b) eating, and (c) drinking, obtained from the same animal and noseband sensor.

surement, pressure value, triaxial acceleration values, ambient temperature value, time of last pressure peak detection, and preliminary classification of the detected behavior. They can be transferred to a PC and processed as Comma-Separated Values (CSV) files for further evaluation.

2.2. RumiWatch Converter software

The RumiWatch Converter (referred to hereafter as RWC; Itin +Hoch GmbH, Liestal, Switzerland) is a specific software application for user-defined post-processing of RumiWatch measurement data. It executes the analysis algorithms and serves for conversion of recorded pressure data into classified measurement data of animal activity. The basic concept of the RumiWatch algorithm is to generate four classifications for parameters of ingestive behavior based on the noseband sensor pressure data (Fig. 3).

Classification and quantification of jaw movements is based on generic algorithms without animal-specific learning data. During the conversion and classification process, recorded pressure data first undergo a raw classification procedure. Thereby, the analysis algorithm classifies pressure data according to the frequency of jaw movements, e.g., 50–70 chews per minute during rumination, and occurrence of systematic interruptions of jaw movements, e.g., during regurgitation of ruminating boluses, within an analysis period (Fig. 2a). An interval between two pressure peaks that is longer than 3.2 s, is registered as a ruminating bolus. The total analysis period for raw classification of pressure data is 60 s. A classification update is made every 10 s. Three consecutive 10-s intervals of the same behavior classification are needed for final classification of the analyzed minute according to the prevailing activity, i.e., either rumination, eating, drinking, or other activity (any other activity not covered by the previously mentioned behaviors). The output of this procedure contains raw classification summaries in 1-min

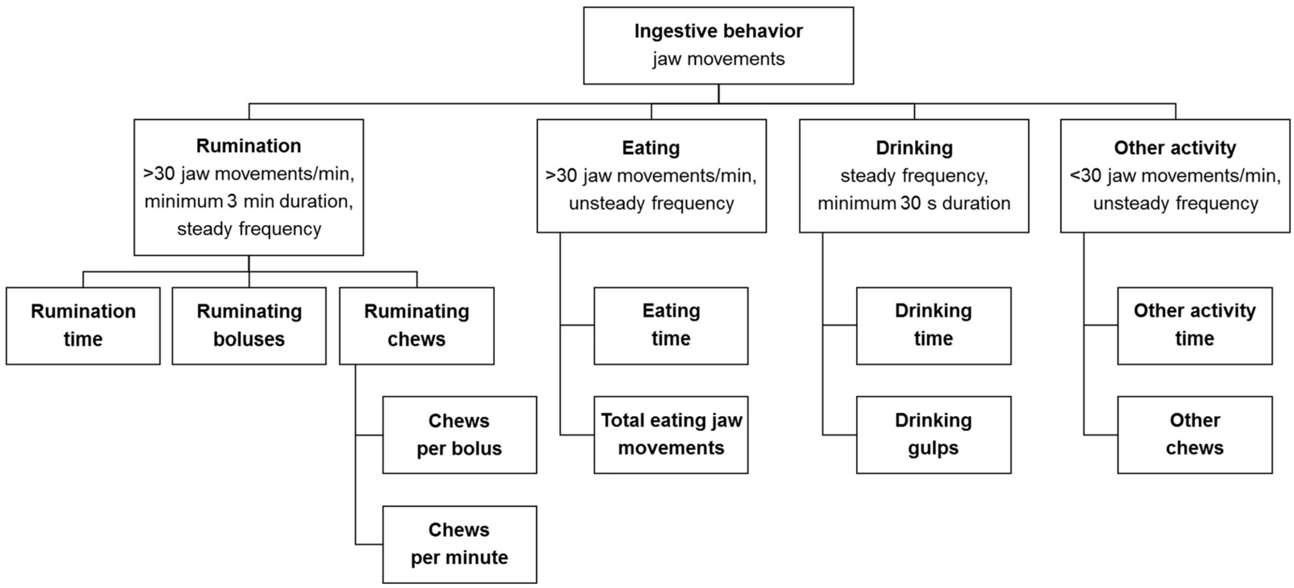

Fig. 3. Classification tree of ingestive behaviors applied by the RumiWatch noseband sensor algorithm.

resolution. As a further conversion and classification option in the software, consolidated summaries of animal activity can be created e.g. with a resolution of one hour. Thereby, the recorded sensor data additionally undergo validity checks contained in the analysis algorithm in order to avoid invalid and defective interpretation of measured values. These validity checks require a minimum resolution of 10 min and can only be applied to consolidated classification data. Hence, they are not effective in the raw classification procedure for data in 1-min resolution. The output of the consolidated classification procedure contains measurement results that represent percentages of behavior time and quantification of jaw movements and boluses within a 1-h interval. As the analysis algorithms have undergone successive development, two releases of the device-specific software for behavior classification are currently available. Software versions used in this validation study were RWC V0.7.2.0 and the subsequently developed RWC V0.7.3.2. Improved validity of detected ruminating activity has been a major focus in the development of RWC V0.7.3.2 due to its high relevance as a health and welfare indicator. The parameters and criteria of the executed validity checks, comparing RWC V0.7.2.0 and RWC V0.7.3.2, are shown in Table 1.

2.3. Experimental procedures

The validation of the RumiWatch noseband sensor was conducted as a field study on commercial dairy farms to investigate the device's and software's suitability for automated behavior classification.

2.3.1. Data collection

The study was performed on 14 Swiss commercial dairy farms. A varying number of experimental animals was randomly selected per farm (range 2 to 18), resulting in a total number of 60 cows of various breeds (9 Holstein Friesian, 6 Red Holstein, 2 Jersey, 34 Brown Swiss, 5 Fleckvieh, 3 Original Braunvieh, 1 Crossbred). The sample consisted of 11 primiparous and 49 multiparous cows with an average of 3.2 (standard deviation 2.1) lactations. The cows were on average 141.4 (standard deviation 97.1) days in milk. The measurements were undertaken during 15 days in August and September. Date and time of observations were chosen randomly. During each observation day, 4 cows were observed. All 60 cows were housed in loose housing systems with cubicles and fed a mixed ration with different proportions of concentrate and forage. In all farms, cows were continuously housed and did not have access to pasture for grazing. Direct observations were performed using a tablet computer (Dell Latitude 10, Dell Inc., Round Rock, Texas, USA). Jaw movements were entered and counted in a spreadsheet (Microsoft Excel 2013, Microsoft Corporation, Redmond, Washington, USA) with a macro for time stamps in tenth of a second resolution (Visual Basic for Applications, Microsoft Corporation, Redmond, Washington, USA). Each jaw movement was registered with its classification of behavior, date and time to a tenth of a second. The beginning and end of ruminating, eating, drinking, and other activity were also registered and, thus, used to determine total duration of these behaviors during the observation periods. All direct observations in this study were done by the same observer (first author) with observational routine based on previous studies. Each cow's behavior was observed continuously for the duration of 1 h, adding up to 3600 observed minutes in total. Direct observation was done according to a pre-defined ethogram for all registered behaviors (Table 2).

In order to allow for time of habituation and to avoid impairments of the animals' normal behavior, direct observations were started approximately 1 h after newly equipping an animal with a RumiWatch noseband sensor. The tablet PC and noseband sensors were time synchronized. Animal behavior could be observed at any location, including feed rack, cubicles, and concrete-floored loafing area, as the observer was able to move freely in order to follow the target animals.

2.3.2. Data preparation

RumiWatch data were converted into 1-min classification summaries (raw classification, i.e., without validity checks) and 1-h classification summaries (consolidated results, i.e., with validity checks, cf. Table 1) using both RWC V0.7.2.0 and RWC V0.7.3.2 for each animal-specific data file. For 1-min raw classification data, the activity within 1 min was summarized and classified according to the dominant activity (either rumination, eating, drinking, or other activity), with simultaneous count of chews and boluses during the respective behavior. Within the 1-h consolidated classification data, measurement results represent percentages of behavior time per hour and quantification of jaw movements and boluses.

Table 1
Parameters and criteria for validity checks integrated into RumiWatch Converters V0.7.2.0 and V0.7.3.2.

Parameter	Validity criterion	Converter version
Ruminating classification	• If bouts of classified ruminating activity are less than a duration of 3 min, this analysis interval is classified as eating activity	V0.7.2.0, V0.7.3.2
Ruminating classification	• Double peaks (peak interval <0.2 s) are ignored for chew count to achieve higher validity of ruminating classification	V0.7.3.2
Bolus detection	• Bolus detection is only activated if current classification is rumination. • Ruminating chews between two detected boluses are counted (chews per bolus). • After detection of a new bolus, counted chews per bolus assist to validate the detection of the respective bolus, executed in the following manner: – <20 chews per bolus: insufficient number of chews, detected bolus is ignored for classification. – ≥20 chews per bolus: valid bolus count. – ≥90 chews per bolus: detection of latest bolus failed, so bolus count is doubled for classification. – ≥150 chews per bolus: detection of last 2 boluses failed, so bolus count is tripled for classification.	V0.7.2.0, V0.7.3.2
Bolus detection	• Minimum of one counted bolus per minute is required for ruminating classification of the analyzed minute	V0.7.3.2

Table 2
Ethogram for the classification of behaviors registered during observations.

Behavior	Description
Ruminating	Chewing and swallowing of a ruminating bolus
Bolus regurgitation	Process of regurgitating a ruminating bolus
Eating	Intake, chewing, and swallowing of feed
Drinking	Putting mouth in water bowl and swallowing water
Other activity	Non-ingestive related activities

Table 3
Definition of classification cases for the types of ingestive behavior (either ruminating, eating, drinking, or other activity).

Predicted classification (RumiWatch Converter)	Actual classification (direct observation)	
	Behavior type present	Behavior type not present
Behavior type present	True Positive	False Positive
Behavior type not present	False Negative	True Negative

Recordings of observation protocols were summarized for the same analysis intervals and resolutions to allow comparison with sensor data.

2.3.3. Statistical analysis

All statistical analyses were conducted in IBM SPSS Statistics 23 (IBM Corporation, Armonk, New York, USA). According to graphical examination and Kolmogorov–Smirnov test of analyzed variables, none of the defined variables was normally distributed ($p < 0.05$); thus, nonparametric tests were used. For evaluation of the raw classification performance, the classification cases shown in Table 3 were defined.

Data in 1-min resolution (raw classification, i.e., without validity checks) were analyzed by calculating sensitivity, specificity, positive predictive value, and accuracy, comparing results of direct observation and sensor data classified by RWC V0.7.2.0 and RWC V0.7.3.2. The parameters included in the analysis were the four different classifications of jaw movements (i.e., either rumination, eating, drinking, or other activity). A confusion matrix approach (Stehman, 1997) was used for classification accuracy assessment of the RWC versions. This specific matrix layout allows visualization of the classification performance, whereby each row of the matrix represents the occurrences in the predicted classification according to the RWC, whereas each column represents the occurrences in the actual classification according to direct observations. Based on the created confusion matrices, the statistical parameters listed in Table 4 were calculated for classifications of the RWC versions.

Thereby, sensitivity describes the proportion of positives that are correctly identified as such. Specificity indicates the proportion of negatives that are correctly identified, whereas the positive predictive value evaluates the proportion of true positives against all positive results. Accuracy is defined as the proportion of true results (both true positives and true negatives) among all obtained results. The Spearman nonparametric correlation coefficient (r_s) was used to analyze the concordance of sensor data in summarized 1-h resolution (consolidated classification, i.e., with validity checks, cf. Table 1) and direct observation. According to Taylor (1990), correlation coefficients were rated as weak ($r_s \leq 0.35$), moderate ($r_s = 0.36–0.67$), strong or high ($r_s = 0.68–0.89$), and very high correlation ($r_s \geq 0.9$). A graphical analysis was conducted by using the Bland–Altman plot (Bland and Altman, 1986). This method evaluates the agreement between two measurement methods, here of behavior classification by direct observation and RWC software. Agreement was expressed as the mean difference between the paired results of software classifications and direct observations (minutes or chews classified by software − minutes or chews classified by direct observation) and plotted against the mean of the paired values ([minutes or chews classified by software + minutes or chews classified by direct observa-

Table 4
Statistical parameters for classification accuracy assessment of the RumiWatch Converter.

Parameter	Equation
Sensitivity	$\text{Sensitivity} = \frac{\text{True Positives}}{\text{Positives}} = \frac{\text{True Positives}}{(\text{True Positives} + \text{False Negatives})}$
Specificity	$\text{Specificity} = \frac{\text{True Negatives}}{\text{Negatives}} = \frac{\text{True Negatives}}{(\text{True Negatives} + \text{False Positives})}$
Positive predictive value	$\text{Positive predictive value} = \frac{\text{True Positives}}{(\text{True Positives} + \text{False Positives})}$
Accuracy	$\text{Accuracy} = \frac{(\text{True Positives} + \text{False Positives})}{(\text{True Positives} + \text{False Positives} + \text{False Negatives} + \text{True Negatives})}$

tion]/2). Additionally, the upper and lower limits of agreement for the 95% confidence interval (CI) were calculated.

3. Results

3.1. Raw classification (1-min resolution)

Raw classification data in 1-min resolution represent the results of the raw classification process exerted by the RWC. The results of counted jaw movements per minute during rumination and eating measured by RumiWatch and direct observation were summarized in box plots (Fig. 4).

The median for ruminating jaw movements per minute was much lower, with 63–64 chews per minute, compared to the median of total eating jaw movements, with 78–79 chews per minute. The interquartile range (75th–25th percentile) followed the same pattern with 10–11 chews per minute for rumination and 27–28 chews per minute for eating. The number of chews per minute comparing rumination and eating differed significantly for all three measurement methods (Mann-Whitney *U* test, $p < 0.001$). The pooled sample of all observed minutes was analyzed with confusion matrices comparing the results of classification by direct observation and the respective RWC version. Confusion matrices for behavior classification of RWC V0.7.2.0 and RWC V0.7.3.2 are shown in Tables 5 and 6, respectively.

The results of the statistical analysis of raw classification data (1-min resolution) are shown in Table 7. Three of the parameters demonstrated a high classification performance for both RWCs. Only the parameter drinking time was found to have a low positive predictive value. However, despite a low sensitivity, specificity for raw classification of drinking time was very high. For RWC V0.7.3.2 there was an indication that sensitivity was higher for rumination time compared to RWC V0.7.2.0. For eating time, the opposite was found. In consequence, RWC V0.7.3.2 was marked by an increased probability for misclassification of other behaviors instead of identifying rumination. Both versions of the RWC showed high robustness for raw classification of other activity time.

3.2. Consolidated classification (1-h resolution)

Results of the statistical analysis of consolidated classification data (1-h resolution) are listed in Table 8. Spearman nonparametric correlation coefficients (r_s) between direct observations and RumiWatch measurements were rated as very high in 10 out of 14 analyzed parameters, high in 3 parameters, and moderate in 1

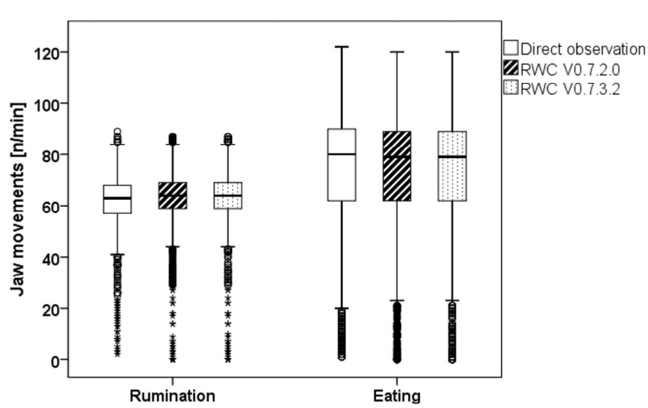

Fig. 4. Comparison of direct observations with the RumiWatch Converters V0.7.2.0 and V0.7.3.2 for the parameters jaw movements per minute during rumination and eating. Raw data are presented as box plots showing the median as bold black line and the boxes as first and third quartiles. The whiskers indicate the 95th and 5th percentiles.

parameter. Highest correlations were found when applying RWC V0.7.3.2. Lowest correlation was calculated for measurement of drinking time using RWC V0.7.2.0.

For consolidated classification, Fig. 5 shows the agreement of the results generated by the two converter versions in comparison with direct observations. The diagram indicates more deviation of rumination time and ruminating chews by RWC V0.7.2.0, whereas these parameters analyzed by RWC V0.7.3.2 showed higher concordance (Table 8).

For all parameters analyzed by Bland–Altman plots (Table 8), the calculated mean differences were lower when using RWC V0.7.3.2, associated with narrower 95% CIs (Table 8; Fig. 6), than when using RWC V0.7.2.0. This result demonstrated the effectiveness of the validity checks introduced in RWC V0.7.3.2 (cf. Table 1).

4. Discussion

The validation showed that the development of the RumiWatch monitoring system was successful. The system was designed to meet the requirements of scientific users. Therefore, it allows recording of ingestive behavior types with full raw data accessibility and post-processing option if a different converter version shall be used at a later time. Thus, collected raw data can be repeatedly evaluated with an updated version of the analysis routines. The obtained accuracy of measurement was high for all analyzed behavior classifications, which is indicative of relatively small systematic errors (cf. Taylor, 1997). The achieved precision of measurement, as expressed by the positive predictive value was satisfactory for classification of rumination, eating, and other activity time, but not so for drinking time. Therefore, classification of drinking behavior is prone to an increased occurrence of random errors. The reinforcement of a particular behavior detection represents a tradeoff that may negatively affect the classification performance for other behavior types. In the present study, this occurred in RWC V0.7.3.2 due to reinforced detection of ruminating behavior. Based on the analysis of raw classification data (1-min resolution), RWC V0.7.3.2 showed a tendency for misclassification and overestimation of behaviors towards rumination, as indicated by lower specificity, positive predictive value, and accuracy for classification of rumination time as compared with RWC V0.7.2.0. The major reason for overestimation of rumination by this software version was the misclassification of eating behavior to rumination, simultaneously resulting in underestimation of eating time (Table 6). Sensitivity and positive predictive value for classification of drinking time was low in both RWC versions (Table 7). Drinking behavior was difficult to classify due to the similarities of the peak profiles of drinking, eating, or idling behavior. Additionally, short duration and low frequency of drinking bouts (drinking time 5.5–6.8 min per day, Huzzey et al., 2005; in 6.6–9.5 bouts, Huzzey et al., 2005; Cardot et al., 2008) represented a challenge in generating sufficient sample size for both development and validation of an analysis algorithm, particularly on individual cow level. Hence, robust detection and extensive examination of validity for measurement of drinking behavior is difficult and requires further research. Comparison of consolidated classification data (1-h resolution) with direct observations revealed higher correlation coefficients when using RWC V0.7.3.2 (Table 8). These results demonstrate the improvement of measuring performance for the consolidated classification due to the validity checks introduced in RWC V0.7.3.2 (cf. Table 1). Particularly for studies requiring consolidated classification of animal behavior or focusing on ruminating activity as an important health parameter, the use of this RWC version is preferable. On the other hand, if the analysis of minute-by-minute data for classification and quantification of jaw movements is of relevance for a conducted study, e.g., in feeding trials,

Table 5
Classification results for 1-min raw classification data for RumiWatch Converter V0.7.2.0 and direct observations.

RumiWatch Converter V0.7.2.0 (min)	Direct observation (min)				Total
	Other activity time	Ruminating time	Eating time	Drinking time	
Other activity time	**1261**	34	96	23	1414
Ruminating time	8	**1095**	49	1	1153
Eating time	56	85	**831**	7	979
Drinking time	32	1	9	**12**	54
Total	1357	1215	985	43	3600

Bold values indicate the true positive classifications.

Table 6
Classification results for 1-min raw classification data for RumiWatch Converter V0.7.3.2 and direct observations.

RumiWatch Converter V0.7.3.2 (min)	Direct observation (min)				Total
	Other activity time	Ruminating time	Eating time	Drinking time	
Other activity time	**1282**	34	98	25	1439
Ruminating time	32	**1164**	267	5	1468
Eating time	33	16	**616**	4	669
Drinking time	10	1	4	**9**	24
Total	1357	1215	985	43	3600

Bold values indicate the true positive classifications.

Table 7
Results of the statistical analysis of RumiWatch raw classification data (1-min resolution) compared with direct observation (pooled sample, n = 60 cows, one continuous observation hour per cow).

Parameter	Converter version	Sensitivity	Specificity	Positive predictive value	Accuracy
Rumination time	V0.7.2.0	0.90	0.98	0.95	0.95
	V0.7.3.2	0.96	0.87	0.79	0.90
Eating time	V0.7.2.0	0.84	0.94	0.85	0.92
	V0.7.3.2	0.63	0.98	0.92	0.88
Drinking time	V0.7.2.0	0.28	0.99	0.22	0.98
	V0.7.3.2	0.21	1.00	0.38	0.99
Other activity time	V0.7.2.0	0.93	0.93	0.89	0.93
	V0.7.3.2	0.94	0.93	0.89	0.94

Table 8
Results of the statistical analysis of the RumiWatch consolidated classification (1-h resolution) compared with direct observation (pooled sample, n = 60 cows, one continuous observation hour per cow).

Parameter	Converter version	Bland–Altman analysis				r_s	Concordance
		Mean difference	Standard deviation	Lower 95% CI	Upper 95% CI		
Rumination time (min/h)	V0.7.2.0	−2.34	6.43	−15.20	10.51	0.91**	Very high
	V0.7.3.2	0.79	3.33	−5.87	7.45	0.96**	Very high
Eating time (min/h)	V0.7.2.0	4.56	7.21	−9.86	18.98	0.86**	High
	V0.7.3.2	2.20	4.78	−7.35	11.76	0.96**	Very high
Drinking time (min/h)	V0.7.2.0	0.57	1.70	−2.82	3.97	0.42**	Moderate
	V0.7.3.2	−0.06	1.13	−2.33	2.20	0.78**	High
Other activity time (min/h)	V0.7.2.0	−3.12	3.66	−10.45	4.21	0.91**	Very high
	V0.7.3.2	−3.12	3.49	−10.10	3.86	0.93**	Very high
Ruminating chews (n/h)	V0.7.2.0	−147.18	378.72	−904.63	610.26	0.92**	Very high
	V0.7.3.2	44.85	174.72	−304.60	394.30	0.97**	Very high
Total eating jaw movements (n/h)	V0.7.2.0	233.22	475.54	−717.86	1,184.29	0.88**	High
	V0.7.3.2	58.85	321.42	−583.99	701.69	0.97**	Very high
Bolus (n/h)	V0.7.2.0	−2.53	7.48	−17.49	12.42	0.93**	Very high
	V0.7.3.2	0.48	4.79	−9.09	10.06	0.97**	Very high

** Correlation is highly significant with $p \leq 0.001$.

the use of RWC V0.7.2.0 is recommended. Here, the accuracy for raw classification of rumination time and eating time was higher than in RWC V0.7.3.2. Although only to a minor degree, the suitability of a RWC version for behavior classification may vary depending on the required temporal resolution and the behavior that is of particular interest for the analysis. However, both converters provide a high standard of validity and measuring performance for eating and ruminating behavior. As a limitation of the presented system compared with the approach described by Rutter et al. (1997) and the acoustic approach used by Ungar and

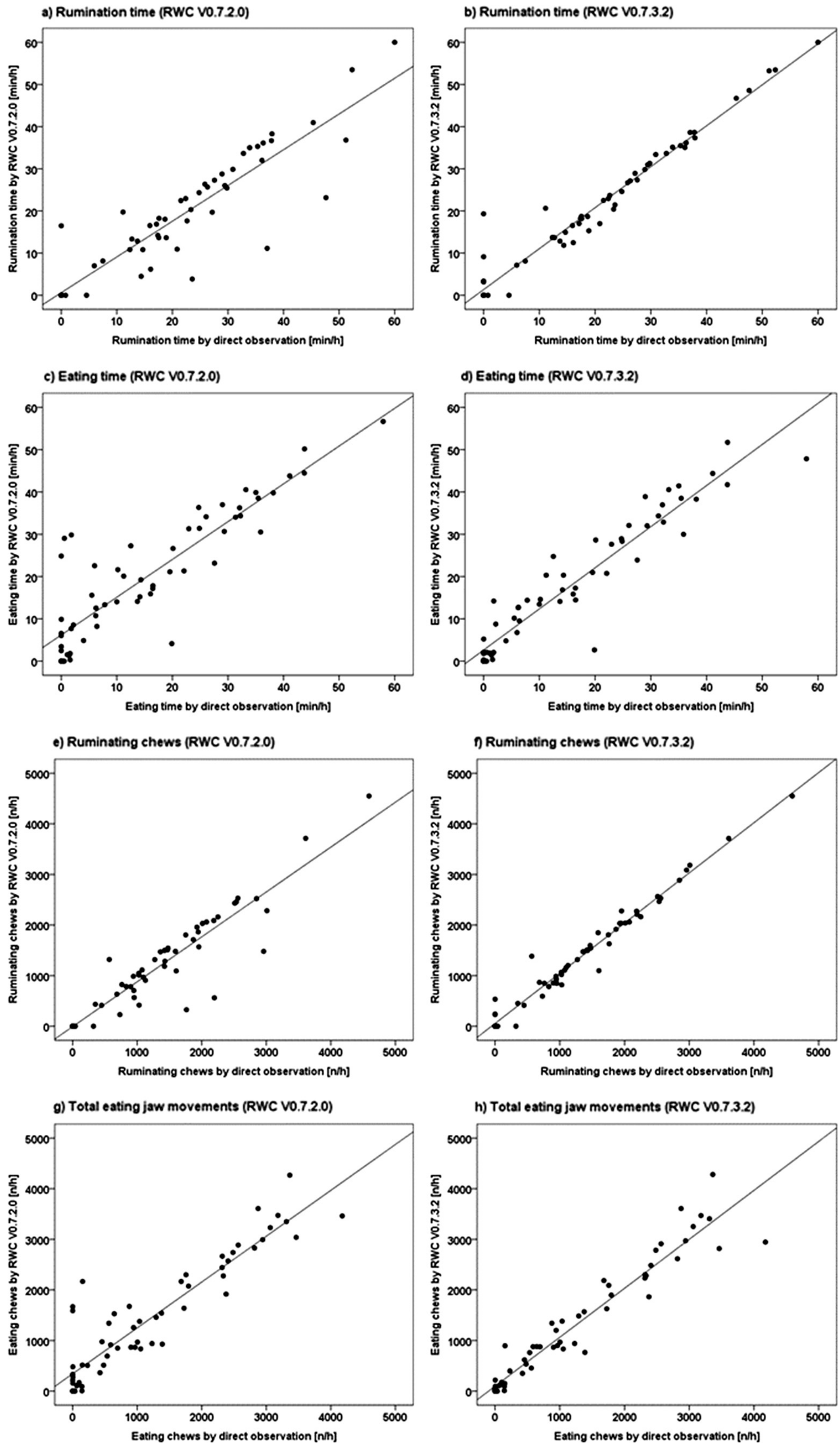

Fig. 5. Correlations between direct observations and RumiWatch Converters V0.7.2.0 and V0.7.3.2 for rumination time (a and b), eating time (c and d), ruminating chews (e and f), and total eating jaw movements (g and h).

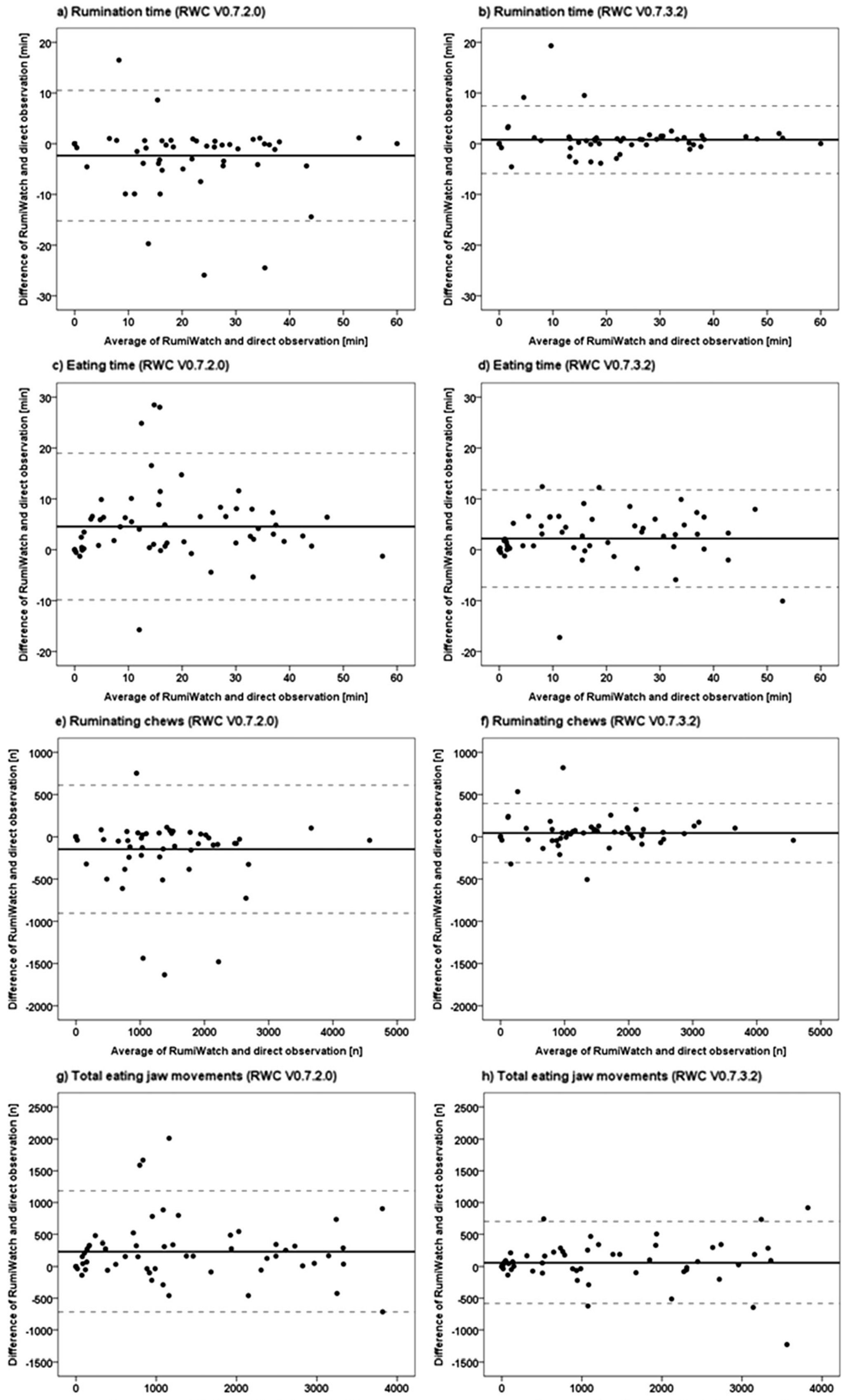

Fig. 6. Bland–Altman plots demonstrating the agreement of direct observations with RumiWatch Converters V0.7.2.0 and V0.7.3.2, analyzed for the parameters rumination time (a and b), eating time (c and d), ruminating chews (e and f), and total eating jaw movements (g and h). Bold lines show the mean difference, dashed lines indicate the lower and upper 95% confidence interval.

Rutter (2006), it cannot discriminate between eating bites, chews, and chew-bites. Hence, the closer analysis of feed intake on pasture appears to be difficult when using the current state of the system's analysis routines. This validation study only used continuously housed cows that were fed mixed rations with no grazing. There is a need for further validation studies where the described system is applied in grazing cows. In a previous state of development, the noseband sensor was evaluated by Ruuska et al. (2016), but only on the basis of duration of chewing activity during eating and rumination, whereas the system's ability to detect and quantify individual chews of these behaviors was not investigated. These authors compared measurements of rumination, eating, and drinking time by the RumiWatch noseband sensor with continuous video observation (n = 6 dairy cows, total sample of 72 h) and found a very dependable relationship for rumination time ($R^2 = 0.93$) and eating time ($R^2 = 0.94$). Comparable results were obtained from the present study, shown by Spearman correlation coefficients of $r_s = 0.91$ (RWC V0.7.2.0) and $r_s = 0.96$ (RWC V0.7.3.2) for rumination time, and $r_s = 0.86$ (RWC V0.7.2.0) and $r_s = 0.96$ (RWC V0.7.3.2) for eating time. The relationship between drinking time recorded by RumiWatch and by video observation found by Ruuska et al. (2016) was poor ($R^2 = 0.20$). This finding was in agreement with the present study, where correlations of automatically measured drinking times were lower than those in the other ingestive parameters, with $r_s = 0.42$ (RWC V0.7.2.0) and $r_s = 0.78$ (RWC V0.7.3.2). In a validation study of a pressure-based measuring system for chewing activity similar to the RumiWatch noseband sensor in our study, the correlation coefficients between the results from the automated system and direct observations were r = 0.99 for the duration of eating and rumination phases (Braun et al., 2013). However, the results of their study are not directly comparable with ours, as Braun et al. (2013) used scan sampling with 1-min sampling intervals, whereas we used continuous observations for obtaining a gold standard (cf. Martin and Bateson, 2007). Continuous direct observation of chewing behavior, as conducted in the current study, represents the best reference method for comparison with sensor measurement. It allows the recording of the type (specific behavior), pattern (duration and frequency of chewing activity), and intensity of chewing behavior (number of chews). The validation method used in several studies was a comparison of automated measurement with scan sampling observations (Grant et al., 1990; Maekawa et al., 2002; Couderc et al., 2006). This observational method is only a representation of activity occurring at intervals and does not trace the continuous automated measurement (Kononoff et al., 2002). Therefore, it was not a suitable method for our analysis.

5. Conclusions

The RumiWatch noseband sensor was successfully developed and validated as a scientific monitoring device for automated measurements of ruminating and eating activity in stable-fed dairy cows. Both system-specific software versions were suitable and showed a high performance for classification of ruminating and eating behavior but less so for the parameter drinking time. The achieved validation results indicate that the measuring performance satisfies scientific requirements. Further research is needed to allow for the differentiation of total eating jaw movements, as the described state of the analysis routines does not enable a separate classification of chews, bites, and chew-bites during eating.

Ethical statement

Ethical approval to conduct this study was obtained from the Thurgau Cantonal Veterinary Office, Switzerland (Approval No. 12.34.03.05). All experimental procedures comply with the ARRIVE guidelines.

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