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3 **Discriminating spontaneous locomotor play of dairy calves using accelerometers**

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14

15 **INTERPRETIVE SUMMARY**

16 Title: Discriminating spontaneous locomotor play of dairy calves using accelerometers

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18 In calves, play behavior is a promising indicator to assess both compromised and  
19 enhanced welfare. However, quantifying play is difficult due to its rare and irregular  
20 occurrence. We aimed to validate 1 Hz accelerometer recordings to measure locomotor play  
21 of dairy calves in their home-pens. Accelerometer data were combined into 10 s periods and  
22 periods were categorized as PLAY/NOPLAY using quadratic discriminant analysis.

23 Comparing these periods with behavior recorded from video, play was correctly classified in  
24 79% of cases. Based on a correlation of  $r_P=0.87$  with observed play intervals, it may be used  
25 as a proxy to replace behavior observations.

## ABSTRACT

26  
27 Play behavior is a promising welfare indicator in dairy calves as it decreases in negative  
28 situations such as pain or hunger and increases in positive contexts such as in appropriate social  
29 environment. Directly measuring play is time consuming as it is performed in irregular bouts  
30 and can be inconsistent over days. To facilitate automatic recording of play, previous studies  
31 fitted tri-axial accelerometers to the hind legs of calves, measuring the velocity of movements  
32 in large arenas, and reported high correlations between vertical axis peak duration and the  
33 duration of locomotor play. The current study aimed at validating accelerometers for recording  
34 spontaneous locomotor play in the calves' home-pens over longer periods of time. Data were  
35 collected from 48 Holstein Friesian calves at either four or eight weeks of age, housed in groups  
36 of three in pens of 10 m<sup>2</sup>. Acceleration at the vertical axis of the hind leg was recorded at a rate  
37 of 1 Hz. One active time period for each calf was randomly selected (mean duration  $\pm$  SD = 34  
38  $\pm$  9 min). From video of the corresponding time period, frequency of locomotor play events  
39 consisting of run, turn and buck/buck-kick was recorded using behavior sampling. Combined  
40 counts of play events were highly correlated ( $r_p = 0.91$ ) with counts of peaks in acceleration.  
41 However, for calves with higher levels of locomotor play, this method underestimated the  
42 extent of play. Alternatively, run, turn and buck events obtained from video were transformed  
43 into a binary response by creating intervals of 10s and then classifying each 10s interval as  
44 comprising events of play (PLAY) or not comprising events of play (NOPLAY). The  
45 corresponding accelerometer data for all 10s periods, equaling 10 consecutive readings each,  
46 were classified into PLAY or NOPLAY with quadratic discriminant analysis. 79% of periods  
47 with locomotor play were correctly classified. Counts of observed play intervals correlated with  
48 the counts of play periods from accelerometers at  $r_p = 0.87$ , but the discriminant analysis  
49 consistently overestimated play. In conclusion, accelerometer measurements at 1 Hz (in 1 s  
50 intervals) and at the vertical axis alone cannot be used to exactly quantify absolute levels of  
51 locomotor play in the home-pen. However, counts of peak accelerations can provide a rough

52 estimate of inter-individual differences in play events and discriminant analysis can be used as  
53 a proxy for one-zero sampling of inter-individual differences in locomotor play.  
54 **Key words:** automated measuring, acceleration, behavior classification, dairy calf

## INTRODUCTION

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In the past decade, accelerometers have found increasing application in farm animal research. The use of accelerometers facilitates data collection as automatic recording can circumvent time and resource intensive behavior observations. In calves, accelerometers have been primarily employed to record general activities. For example lying, standing or locomotion of dairy calves have been recorded using accelerometers to detect early behavioral signs of respiratory diseases (Swartz et al., 2017) and of neonatal diarrhea (Sutherland et al., 2018b). Moreover acceleration measurements have been used to quantify lying and standing when studying effects of social housing on weaning (Overvest et al., 2018) and determining effects of different disbudding methods on lying behavior (Sutherland et al., 2018a). While the accuracy of recording general activities from accelerometers is high, the validation of recording specific behaviors such as feeding and ruminating is still in progress (e.g. Roland et al., 2018).

In calves, play behavior is a promising indicator to assess both compromised welfare, e.g. pain after disbudding (Mintline et al., 2013) or hunger after weaning off milk reduced play (Krachun et al., 2010, Miguel-Pacheco et al., 2015), and enhanced welfare, e.g. group housing increased play (Valníčková et al., 2015). However, calves perform spontaneous play for only a few minutes per day (Jensen et al., 2015) at irregular intervals (Fraser and Duncan, 1998). Thereby quantification of play from observation is usually accomplished either through continuous recording of durations or events (e.g. Jensen et al., 2015, Miguel-Pacheco et al., 2015) or through one-zero sampling of the presence of play in certain sample intervals (e.g. Valníčková et al., 2015). These challenges associated with measuring play behavior raise the interest in automatic recording techniques. In previous studies, accelerometers were used to automatically record locomotor play of calves, however the recordings were conducted in large arenas and for a short time only. Rushen and de Passillé (2012) found correlations of up to  $r_s = 0.88$  between the duration of running and the sum of total acceleration in all three axes

81 and Luu et al. (2013) found correlations of up to  $r_p = 0.98$  between the duration of locomotor  
82 play (running plus jumping/kicking) and the sum of the percent of peaks (3 g or higher) of all  
83 axes. In both studies acceleration was recorded at a high rate of 33 Hz and in all three axes,  
84 limiting the recording duration to 10 min due to the memory capacity of the accelerometers  
85 (HOBO Pendant G Acceleration Data Logger, Onset Computer Corporation, Pocasset, MA,  
86 USA). With the intention of assessing a longer recording duration, Luu et al. (2013) simulated  
87 a sampling frequency of 1 Hz by taking every 33rd acceleration reading on one axis only and  
88 found a correlation of  $r_p = 0.92$  between the percent of peaks on the vertical axis and the  
89 duration of locomotor play. In order to test the practical application of measuring spontaneous  
90 locomotor play over the duration of many hours, the current study aimed to validate the use of  
91 accelerometers to measure play behavior in the home-pens of calves at low recording rates.  
92 Specifically, our objectives were using recordings at 1 Hz on the vertical axis (1) to test  
93 whether counts of peak accelerations can accurately estimate events of locomotor play and (2)  
94 to determine whether classifying periods of acceleration readings into PLAY/NOPLAY can  
95 reliably measure play behavior recorded by one-zero sampling from video.

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## MATERIAL AND METHODS

98 All data were collected at the Netluky Research Station at the Institute of Animal Science in  
99 Prague/Czech Republic between August 2016 and April 2017. The study was approved by the  
100 Institutional Animal Care and Use Committee of the Institute of Animal Science in Prague  
101 and the Czech Central Committee for Protection of Animals, Ministry of Agriculture (permit  
102 number 27356/2016-MZE-17214).

103

### *Animals and Housing*

104 The 48 Holstein Friesian-calves (20 female, 28 male) reported on here were a subset of a  
105 larger study using 72 calves. They were housed in an uninsulated barn with wind-shields in 24  
106

107 groups of three. Pens were 10.1 m<sup>2</sup> with a straw-bedded lying area of 4.2 x 1.4 m and a  
108 concrete activity and feeding area of 3.5 x 1.2 m. Calves entered group-housing at an average  
109 age of 13.3 ± 3.1 days (mean ± SD) with groups entering the experiment consecutively. Calf  
110 allocation to groups was balanced for sex, age and weight. For the purpose of another  
111 experiment calves were fed either 6 liters of milk daily throughout the experiment or they  
112 received 9 liters per day at week 4 and the provision continuously increased to 12 liters at  
113 week 6. All calves received three milk meals per day in teat buckets. All calves received 3  
114 liters of milk in the morning. Calves with a low milk allowance received 1.5 liters of milk per  
115 meal at midday and in the evening. Calves with a high milk allowance received 3 liters  
116 continually increasing to 4.5 liters of milk per meal at midday and in the evening. Calves had  
117 ad libitum access to water, concentrates and hay offered in buckets. Among the 72 calves, two  
118 focal calves per group were randomly selected with observations of one calf taking place at 4  
119 weeks and the other at 8 weeks of age. Calves weighed 57.5 ± 5.7 kg (mean ± SD) at 4 weeks  
120 and 88.3 ± 12.4 kg at 8 weeks.

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### 122 *Acceleration measurements*

123 Accelerometers (HOBO Pendant G Acceleration Data Logger, Onset Computer Corporation,  
124 Pocasset, MA, USA; product specifications are described in detail in Luu et al. (2013)) were  
125 fitted to the rear side of both hind legs of calves using elastic cohesive bandages.

126 Accelerometers were attached vertically to the leg such that the x-axis was perpendicular to  
127 the ground. The accelerometers were set to measure readings on the vertical axis at a rate of 1  
128 Hz (1 sample/s), allowing recording of acceleration every second for 18.1 hours. Acceleration  
129 was recorded from 05.00 until 23.04 on two consecutive days per testing week with the  
130 accelerometer on the right leg recording day 1 and on the left leg recording day 2. Calves  
131 wore accelerometers for approximately 66 hours per testing week (from the evening before  
132 until the morning after the testing days). Programming of accelerometers was performed using

133 an optical infrared base station with USB interface and the HOBOWare Pro Software (Version  
134 3.7.8; Onset Computer Corporation, Pocasset, MA, USA) with the starting time set in  
135 advance.

136

### 137 ***Behavior observation***

138 Behavior of calves was video recorded for 48 hours per testing week using one camera per  
139 pen (VCC-HD2300P, Sanyo, Japan; FW2220R-Z, Dahua Technology Co., China; HDC-  
140 SD99, Panasonic, Japan) and infrared radiators (RM50-AI-50, Raytec, UK; LIR-T80 and  
141 LIR-T60, IR LAB Surveillance Tech, Taiwan). Based on the graphic display of downloaded  
142 acceleration values, using the plot-function of the HOBOWare Pro Software, lying and active  
143 phases could be clearly distinguished. Therewith one activity bout of approx. 30 min was  
144 selected for each calf. Activity bouts were selected in a time span between 05.00 and 20.00  
145 when accelerometer recordings were available and video recordings allowed easy distinction  
146 of behaviors due to daylight hours. The week and day of the selected activity bout was  
147 randomized for each focal calf. Selection of activity bouts was balanced across different times  
148 of the day and start time of selected bouts ranged from 06.04 until 19.23. The duration of  
149 selected activity bouts was  $34.3 \pm 9.2$  min (mean  $\pm$  SD). For individual recognition calves  
150 were marked across their backs and sides with animal marking sticks. Behaviors categorized  
151 as locomotor play are described in Table 1. The criterion interval for halts in between running  
152 events was set to 1 second based on visual assessment of a log survivorship plot. Events of  
153 locomotor play behavior were continuously recorded by one person using the Mangold  
154 INTERACT video analysis software (Version 16.1.5.8). Intra-observer-reliability was  
155 measured from 3 randomly selected activity bouts of  $41.7 \pm 8.0$  min each (mean  $\pm$  SD)  
156 assessed two times. A Wexler's ratio was calculated from the number of agreements (i.e. the  
157 number of locomotor play events that were correctly scored within one second in both  
158 recording sessions x 2) divided by the number of possible agreements (i.e. the total number of



159 locomotor play events scored in both sessions; e.g. used in Wathan et al. 2015). Wexler's ratio  
160 was assessed for each activity bout individually, with an average agreement ratio of 0.84.  
161 Continuous recording was transformed into one-zero sampling by creating sample intervals of  
162 10 s and classifying them according to presence or absence of locomotor play events within  
163 the interval.

164

### 165 *Data analysis*

166 All statistical analyses were performed in SAS 9.4. We analyzed the acceleration data  
167 according to two methodologies:

168

169 ***Peak acceleration method (PEAK)***. We used Pearson correlations to assess the strength of  
170 association between counts of peak measurements of acceleration and counts of observed  
171 locomotor play events. Counts of peak accelerations were calculated for different upper and  
172 lower thresholds of acceleration values in steps of 0.1 g (e.g. counts of values  $\geq 3.2$  g, 3.1 g,  
173 3.0 g,... and  $\leq -3.2$  g, -3.1 g, -3.0 g,...). Pearson correlations of all 1056 combinations (32  
174 thresholds of  $\geq 0$  g times 31 thresholds of  $< 0$  g) of counts of peaks applying different upper  
175 and lower thresholds with counts of locomotor play were calculated. Therewith, the best  
176 combination of threshold values of acceleration to predict locomotor play was identified as  
177 counts of peaks of  $\geq + 1.6$  g and  $\leq - 3.0$  g. While the distribution of data was right-skewed and  
178 did not visually conform to the assumption of normality for parametric measures of  
179 association, the data distribution was unimodal. Three outliers were visually detected using a  
180 Cook's Distance plot, though no outlier with leverage was visually identified in the outlier  
181 and leverage diagnostics (leverage and studentized residuals).

182

183 ***Classifier method (CLASS)***. We used quadratic discriminant analysis to predict a categorical  
184 response (Kuhlenkasper and Handl, 2017), i.e. the occurrence of locomotor play in each

185 period (10 s fragment of observations) based on classifiers (predictor variables describing  
186 acceleration values in each period (James et al., 2015)). As discriminant analysis requires two  
187 sets of data, one set to train the discriminant function and one set to test its predictions, we  
188 divided the recorded activity bouts in half. Therefore the accelerometer data were combined  
189 to 10 s periods, resulting in 10 measurements per period. Subsequently the periods were  
190 alternately allocated to a training data set or a testing data set (testing data set: n=48, mean  
191 number of periods  $\pm$  SD = 102.3  $\pm$  26.9). The presence (PLAY) or absence (NOPLAY) of  
192 locomotor play in each period was identified from video observation and used as the gold  
193 standard. For each period the following metrics were calculated as classifiers derived from the  
194 original value (OV) or change in values (CV =  $x_i - x_{i-1}$ ) e.g. minimum, maximum, mean,  
195 median, quartiles, variance, total sum; a full list is provided in Supplemental Table S1.  
196 Relevant classifiers were then visually preselected from boxplots of PLAY and NOPLAY  
197 from the training data set when the interquartile range of NOPLAY was low with little to no  
198 overlap with PLAY and when outliers were not widely dispersed. A quadratic discriminant  
199 function was then developed with classification probabilities based on the proportional  
200 occurrences of how often PLAY and NOPLAY were scored in the training data set, i.e. 97%  
201 of periods displaying NOPLAY and 3% of periods displaying PLAY. With the testing data set  
202 the predictive abilities of the discriminant function were assessed. Discriminant functions  
203 with different combinations of classifiers were tested and the combination of classifiers with  
204 the highest sensitivity and specificity was selected. The relevant classifiers included in the  
205 final discriminant function are displayed in Table 2. Discriminant analysis assumes a  
206 Gaussian distribution from observations of each class (James et al., 2015). The present data of  
207 the values of classifiers could not be assumed to be normally distributed nor could data be  
208 transformed to fit the underlying assumptions of normality. We were able to circumvent this  
209 issue by dividing the data set into two halves, a training data set and a testing data set.

210 Therewith the performance of the discriminant function was not contingent on the data  
211 distribution and could be independently verified.

212

213 ***Comparison of PEAK and CLASS.*** In order to directly contrast the outcome of the two  
214 methodologies on the basis of the same set of data, we calculated PEAK and CLASS with the  
215 testing data set only ( $n = 48$ ; mean duration  $\pm$  SD =  $17.1 \pm 4.6$  min). To assess the strength of  
216 association between the measures of acceleration and the observed locomotor play, a Pearson  
217 correlation of counts of peaks resulting from the PEAK method and counts of observed  
218 locomotor play events was calculated. Likewise, a Pearson correlation of counts of PLAY  
219 periods resulting from the CLASS method with counts of observed locomotor play intervals  
220 from one-zero sampling was calculated. In order to assess the magnitude of disagreement and  
221 facilitate the detection of trends, we produced Bland-Altman plots. The plots depict the  
222 average of the acceleration measure and the observation on the x-axis and the difference  
223 between the acceleration measure and the observation on the y-axis (Altman and Bland,  
224 1983). Bland-Altman plots were produced for both methodologies of analysis and compared  
225 visually.

226

227

## RESULTS

228 When assessing play by continuous recording of frequencies, calves performed 5.3 events of  
229 locomotor play per 30 min observation period (SD = 7.3; range = 0 - 27). The Pearson  
230 correlation with counts of peaks of  $\geq + 3.0$  g and  $\leq - 3.0$  g from the corresponding  
231 accelerometer data, as described by Luu et al. (2013), was 0.83 ( $P < 0.01$ ). However, we  
232 attained the highest correlation with counts of locomotor play when using counts of peaks of  
233  $\geq + 1.6$  g and  $\leq - 3.0$  g ( $r_p = 0.91$ ,  $P > 0.01$ ; Figure 1). The respective scatter plot (Figure 1)  
234 illustrates a strong linear relationship of both measurements, but an unequal rate of increase of  
235 counts of peaks with counts of play is noticeable. The Bland-Altman plot (Figure 2) further

236 emphasizes the uneven distribution across the range of locomotor play as higher counts of  
237 locomotor play events were increasingly underestimated by the peak acceleration method,  
238 demonstrating that the number of play events and the number of accelerometer peaks did not  
239 directly correspond to each other, i.e., they are not on the same scale. The mean deviation of  
240 peak measurements from observed play events amounted to  $-1.90 \pm 4.42$ .

241 Alternatively, when recording locomotor play with one-zero sampling, calves performed play  
242 in 2.7 periods per observation (SD = 3.5; range = 0 - 16). From the accelerometer data, we  
243 estimated the number of play periods using the classifier method with the outcome displayed  
244 as contingency table (Table 3). It follows that CLASS overestimates the number of PLAY  
245 periods. CLASS achieved a precision of 0.95 (= proportion of correctly classified periods), a  
246 sensitivity of 0.79 (= proportion of correctly classified true positives) and a specificity of 0.96  
247 (= proportion of correctly classified true negatives). Counts of PLAY periods identified with  
248 CLASS highly correlated with counts of observed PLAY periods recorded from video ( $r_p =$   
249  $0.87$ ;  $P < 0.01$ ; Figure 3). The scatter plot (Figure 3) illustrates a strong linear relationship of  
250 both measurements but indicates an intercept and concomitant overestimation of PLAY  
251 periods by the CLASS method. The number of accelerometer-identified PLAY periods  
252 surpasses the number recorded visually by  $3.65 \pm 2.42$  periods; nonetheless the Bland-Altman  
253 plot (Figure 4) shows an evenly distributed deviation of the two measurements across the  
254 range of counts of PLAY periods.

255

256

## DISCUSSION

257 With this study we aimed at providing an approach to automatically record locomotor play of  
258 calves in their home-pen and for long durations using acceleration measurements. In previous  
259 studies accelerometers have been validly used to record durations of lying and standing in  
260 calves (Bonk et al., 2013, Swartz et al., 2016). Similarly in the current study we were able to  
261 easily distinguish between lying and standing on the vertical axis, with values of lying

262 fluctuating around 0 g and values of standing around - 1 g, depending on the position of the  
263 hind leg. Therefore with - 1 g as the center of fluctuation, measuring play with peaks of  $\geq +$   
264 1.6 g and  $\leq - 3.0$  g is sensible. We reason that peaks had not reached + 3.0 g, as reported by  
265 Luu et al. (2013), because the smaller dimensions of the home-pens in comparison with a  
266 large arena did not permit calves to consistently reach accelerations of a similarly high level.  
267 Thus small spaces can restrict the magnitude of movement and also fragment the occurrence  
268 of play (Jensen et al. 1998). Nevertheless we cannot draw conclusions on any space allowance  
269 between our home-pen and the arena of Luu et al. (2013) as this was not part of our  
270 investigation. Moreover locomotor play consists of rapid motions of the hind legs for short  
271 durations and is often nested within short time intervals. Therefore recordings at 1 Hz and on  
272 one axis may be too infrequent to accurately capture locomotor play events in the home-pen,  
273 resulting in the unequal increase and accretive underestimation of higher frequencies of play  
274 events of the PEAK-method, as visualized in the Scatter plot and Bland-Altman plot.  
275 Nevertheless, the high correlation of peak accelerations and observed play events elucidates a  
276 strong link between the two recording methods. Thus, while the PEAK-method cannot record  
277 the duration of play in absolute terms, it can produce an approximate estimation of play levels  
278 and allows the comparison of relative differences between calves in standard housing  
279 conditions.

280 In the CLASS method, we used the accelerometer data to simulate the one-zero observational  
281 method by merging the recordings to 10 s periods, thus ensuring the use of repeated measures  
282 and circumventing the need to count individual peaks above/below a certain threshold. This  
283 allowed us to view acceleration values in context, integrated with the values preceding and  
284 following them. We derived classifiers from combined values e.g. mean of two highest values  
285 or variance to mathematically describe the 10 acceleration measures per period and highlight  
286 the differences between PLAY and NOPLAY. Thereby we classified brief time spans  
287 according to the presence or absence of locomotor play within these 10 seconds. The use of

288 original individual acceleration values e.g. the mere minimum or maximum value would have  
289 resulted in a lower sensitivity to correctly identify PLAY periods. Such an approach has been  
290 previously successfully implemented in accelerometer validation regarding sheep gait,  
291 describing periods with relative frequencies of integers e.g. the number of high frequency  
292 acceleration readings between - 4 and - 3 per period divided by all readings of the period  
293 (Radeski and Ilieski, 2017). Other studies described periods using movement metrics e.g.  
294 mean, variance and inverse coefficient of variation (Watanabe et al., 2008) or signal  
295 magnitude area, average intensity and average entropy (Barwick et al., 2018). However, in  
296 these studies acceleration was recorded at a higher rate. Recording at a higher rate would have  
297 also allowed for classifying shorter periods. For example Radeski and Ilieski (2017) recorded  
298 at 33 Hz and classified periods of three seconds.

299 CLASS correctly discriminated 79% of periods with an occurrence of locomotor play, but at  
300 the same time overestimated play by approximately 200% (out of 304 play periods identified  
301 by CLASS, 102 periods were true positives and 202 periods were false positives). Similarly  
302 other accelerometer models consistently overestimated locomotor behavior e.g. Swartz et al.  
303 (2016) overestimated stepping by 18% and Trénel et al. (2009) consistently overestimated  
304 moving activity with a ratio of probability of correct negatives to correct positives of 7.57  
305 ( $PV^- = 0.98$ ,  $PV^+ = 0.13$ ). Thus while the number of classified play periods is strongly  
306 associated with counts of observed play intervals, overall the classifier method overestimates  
307 locomotor play in absolute terms and produces an intercept by adding 3.7 play periods to each  
308 observation. However, the Bland-Altman plot shows a rather consistent and evenly  
309 distributed deviation across the range of number of play intervals observed without indication  
310 of a directed effect. Hence, while CLASS cannot accurately measure locomotor play, it can be  
311 used as a proxy. After factoring in the consistent overestimation, it assesses the number of  
312 play periods close to the scale of one-zero sampling and thus allows comparing absolute  
313 differences between individuals. With these results we offer a feasible approach to assess

314 spontaneous locomotor play in home-pens of calves using an affordable and commercially  
315 available accelerometer model for durations of many hours or perhaps even days.  
316 Nevertheless these results may only be valid for the housing conditions investigated and  
317 further studies are needed to validate this approach under e.g. different space allowances. A  
318 prerequisite to classify periods with discriminant analysis is to use shorter subsets of behavior  
319 recordings as a training data set. In the current study only active periods of animals were  
320 included in the analysis. In order to apply the classifier method to the full data set it is  
321 necessary to either preselect only active periods or to include lying bouts in the training data  
322 set. Therewith it is feasible to train the discriminant function with the selected classifiers and  
323 thereafter to apply it to the entire recordings of acceleration.

324 We must stress that our proposed approach with recording at a frequency of 1 Hz can only be  
325 used as an approximate estimation of locomotor play. A higher level of accuracy could be  
326 achieved by increasing the rate of recording. Measuring acceleration at the highest rate (33  
327 Hz) allowed de Passillé et al. (2010) to measure the interstep interval and accurately  
328 distinguish between different gait patterns. Radeski and Ilieski (2017) were able to achieve  
329 high accuracy in classifying 3 s periods of walking, trotting and galloping in sheep with  
330 discriminant analysis, when recorded at a rate of 33 Hz. In the current study the recording rate  
331 was limited by its data storage capacity, however Le Roux et al. (2018) achieved a 469-fold  
332 reduction in memory requirement when classifying lying, standing and walking on the  
333 accelerometer rather than storing raw data. Thus, the proposed approach is easily applicable  
334 and inexpensive with the available resources, however there are numerous options to improve  
335 the accuracy of recording by availing technical advancements.

336

337

## CONCLUSION

338 Using the peak acceleration method, the acceleration of calves' hind legs measured at a rate of  
339 1 Hz can be used to obtain an approximate estimation of inter-individual differences in the

340 occurrence of locomotor play events. Quadratic discriminant analysis can replace  
341 observational one-zero sampling, when based on indirect movement metrics obtained from  
342 10-second-periods of raw accelerometer data. This alternative method may be more accurate  
343 in quantifying the inter-individual differences in locomotor play of dairy calves in their home-  
344 pens as it reveals less biased estimates across different levels of play. If the accurate  
345 measurement of absolute levels of behavior is the ultimate aim of automatic recording, a  
346 sensor with higher memory capacity must be found.

347

348

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352

353

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432 **Table 1.** Ethogram of locomotor play derived from Jensen et al. (1998) and Jensen and Kyhn  
433 (2000)

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<b>Type of locomotor play</b>	<b>Description</b>
<b>Running</b>	Rapid gait with phase of suspension in the air. Minimum of 2 consecutive suspension movements in a forward direction. Running is counted as a new event after 1 second break.
<b>Turning</b>	The two forelegs are lifted from the ground and stretched forward, as the forepart of the body is elevated and turned to one side. Movement upwards and sideward for a minimum of 90 degrees. Occurrence is scored during running bouts.
<b>Bucking/Buck-kicking</b>	Simultaneous lifting of hind legs, claws are raised to a level as high as, or higher than tarsal joints in a standing position. One or both hind legs may be kicked in a posterior or lateral direction. Occurrence is scored during running bouts.

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434

435 **Table 2.** Descriptions and equations of the classifiers included in the final discriminant  
 436 function. Means  $\pm$  standard deviation of the classifiers are shown for the periods of the testing  
 437 data set identified as PLAY or NOPLAY from video. OV = original values, CV = change in  
 438 values, PLAY = period with presence of locomotor play, NOPLAY = period with absence of  
 439 locomotor play

Classifier	Equation	NOPLAY	PLAY
<b>OV: Mean of two highest acceleration measurements</b>	$\frac{\max(x) + \max_2(x)}{2}$	$-0.89 \pm 0.21$	$0.04 \pm 0.99$
<b>OV: Mean of two lowest acceleration measurements</b>	$\frac{\min(x) + \min_2(x)}{2}$	$-1.06 \pm 0.20$	$-1.85 \pm 0.70$
<b>OV: Variance</b>	$\frac{\sum(x - \mu)^2}{10}$	$0.03 \pm 0.10$	$0.74 \pm 0.80$
<b>CV: Maximum of absolute value of change in acceleration measurements</b>	$\max( \Delta x )$	$0.26 \pm 0.48$	$2.41 \pm 1.45$
<b>CV: Mean of change in acceleration measurements</b>	$\frac{1}{10} \sum \Delta x_i$	$-0.00 \pm 0.03$	$-0.01 \pm 0.12$
<b>CV: Total sum of absolute values of change in acceleration measurements</b>	$\sum  \Delta x_i $	$0.66 \pm 1.15$	$6.96 \pm 4.78$

440

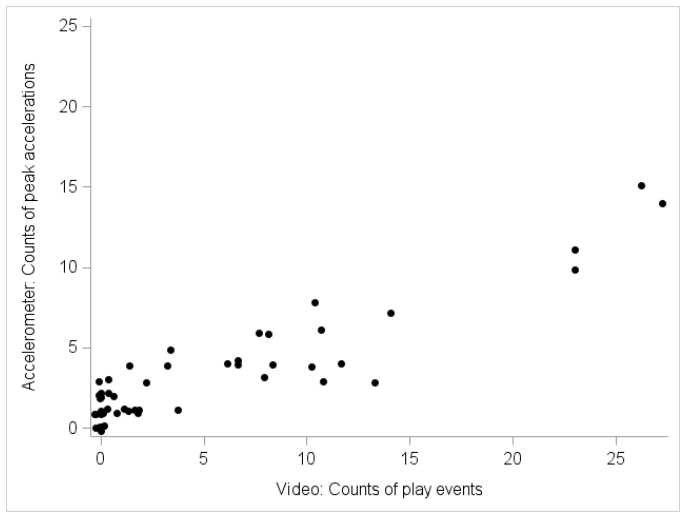
441 **Table 3.** Contingency table with number of periods identified with the classifier method  
 442 (CLASS) as PLAY (event of locomotor play occurring in this period) and NOPLAY (no  
 443 event of locomotor play occurring in this period)

<b>Observed behavior</b> <b>(Video)</b>	<b>Predicted behavior</b> <b>(CLASS)</b>		
	<b>NO</b>	<b>PLAY</b>	<b>Sum</b>
<b>NOPLAY</b>	4591	202	4793
<b>PLAY</b>	27	102	129
<b>Sum</b>	4618	304	4922

444

445 **Figure 1.** Relationship between counts of peak accelerations ( $\geq 1.6$  g and  $\leq 3.0$  g; PEAK) and  
446 counts of locomotor play events observed from video (n = 48 calves). Jitter function was used  
447 in the graph to make multiple identical values more visible

448 Größbacher Figure 1

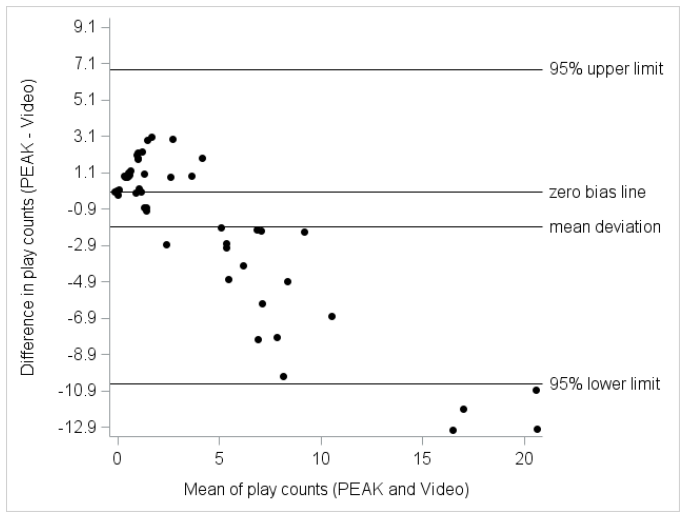


449



450 Figure 2. Bland-Altman Plot of the difference in the assessment of locomotor play recorded  
451 with accelerometers and video observation compared with the mean of both assessments  
452 (PEAK = Peak acceleration method; n = 48 calves). Confidence intervals were estimated at  
453 6.8 at the 95% upper limit and - 10.6 at the 95% lower limit. Jitter function was used in the  
454 graph to make multiple identical values more visible

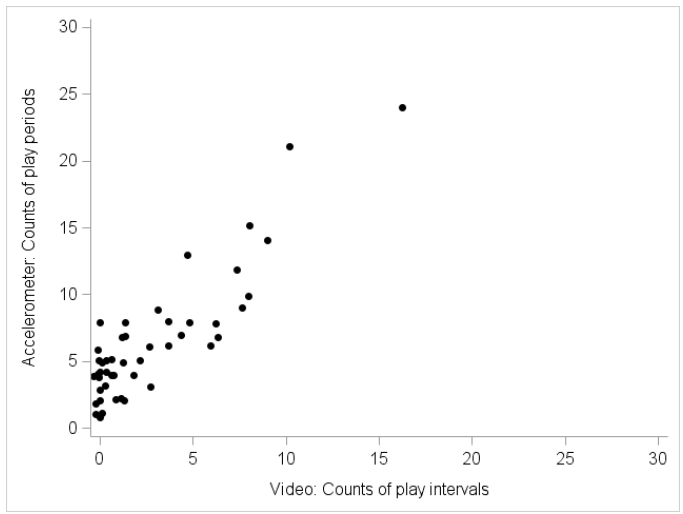
455 Größbacher Figure 2



456

457 Figure 3. Relationship between counts of periods with locomotor play identified with  
458 accelerometers (CLASS = classifier method) and counts of sample intervals with locomotor  
459 play observed from video (n = 48 calves). Jitter function was used in the graph to make  
460 multiple identical values more visible

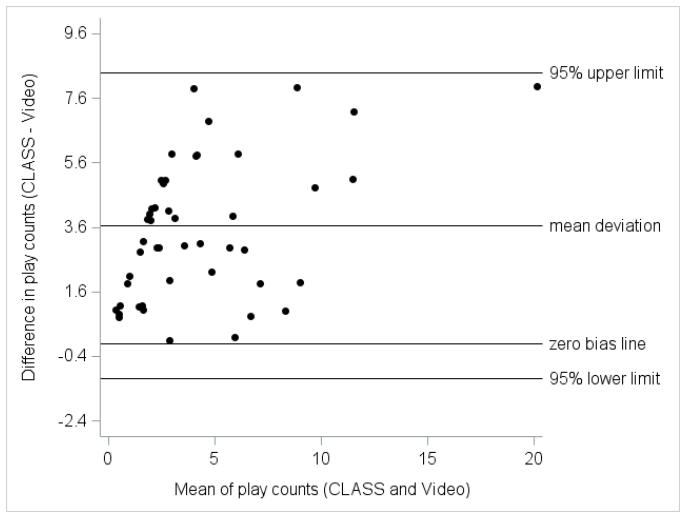
461 Größbacher Figure 3



462

463 Figure 4. Bland-Altman Plot of the difference in the assessment of locomotor play periods  
464 identified with accelerometers and locomotor play intervals from video observation compared  
465 with the mean of both assessments (CLASS = Classifier method; n = 48 calves). Confidence  
466 intervals were estimated at 8.4 at the 95% upper limit and - 1.1 at the 95% lower limit. Jitter  
467 function was used in the graph to make multiple identical values more visible

468 Größbacher Figure 4



469

470 **Supplemental Table S1.** Descriptions and equations of all potential classifiers not included in the final discriminant function. Means  $\pm$  standard  
 471 deviation of the classifiers are shown for the periods of the testing data set identified as PLAY or NOPLAY from video. OV = original values, CV =  
 472 change in values, PLAY = period with presence of locomotor play, NOPLAY = period with absence of locomotor play. Potential classifiers that  
 473 were preselected and tested but not included in the final discriminant function are marked with ‘Yes’

Classifier	Equation	NOPLAY	PLAY	Preselection
<b>OV: Highest acceleration measurement</b>	$\max(x)$	$-0.84 \pm 0.33$	$0.44 \pm 1.30$	Yes
<b>OV: Second highest acceleration measurement</b>	$\max2(x)$	$-0.94 \pm 0.12$	$-0.37 \pm 0.84$	Yes
<b>OV: Mean of two highest acceleration measurements</b>	$\frac{\max(x) + \max2(x)}{2}$	$-0.89 \pm 0.21$	$0.04 \pm 0.99$	Yes
<b>OV: Third quartile of acceleration measurements</b>	$x_{Q0.75}$	$-0.96 \pm 0.08$	$-0.64 \pm 0.50$	No
<b>OV: Mean of acceleration measurements</b>	$\frac{1}{10} \sum x_i$	$-0.98 \pm 0.07$	$-0.93 \pm 0.29$	No
<b>OV: First quartile of acceleration measurements</b>	$x_{Q0.25}$	$-1.00 \pm 0.07$	$-1.24 \pm 0.41$	No
<b>OV: Mean of two lowest acceleration measurements</b>	$\frac{\min(x) + \min2(x)}{2}$	$-1.06 \pm 0.20$	$-1.85 \pm 0.70$	Yes
<b>OV: Second lowest acceleration measurement</b>	$\min2(x)$	$-1.02 \pm 0.10$	$-1.52 \pm 0.69$	Yes
<b>OV: Lowest acceleration measurement</b>	$\min(x)$	$-1.11 \pm 0.33$	$-2.19 \pm 0.86$	Yes
<b>OV: Variance</b>	$\frac{\sum(x - \mu)^2}{10}$	$0.03 \pm 0.10$	$0.74 \pm 0.80$	Yes
<b>OV: Total sum of absolute values of acceleration measurements</b>	$\sum  x_i $	$9.84 \pm 0.63$	$11.32 \pm 2.20$	Yes

<b>CV: Highest change in acceleration measurements</b>	$\max(\Delta x)$	$0.22 \pm 0.43$	$2.01 \pm 1.34$	No
<b>CV: Second highest change in acceleration measurements</b>	$\max 2(\Delta x)$	$0.07 \pm 0.14$	$0.86 \pm 0.81$	No
<b>CV: Third quartile of change in acceleration measurements</b>	$\Delta x_{Q0.75}$	$0.04 \pm 0.07$	$0.50 \pm 0.55$	No
<b>CV: Mean of change in acceleration measurements</b>	$\frac{1}{10} \sum \Delta x_i$	$-0.00 \pm 0.03$	$-0.01 \pm 0.12$	Yes
<b>CV: First quartile of change in acceleration measurements</b>	$\Delta x_{Q0.25}$	$-0.04 \pm 0.08$	$-0.49 \pm 0.53$	No
<b>CV: Second lowest change in acceleration measurement</b>	$\min 2(\Delta x)$	$-0.07 \pm 0.15$	$-0.88 \pm 0.82$	Yes
<b>CV: Minimum of change in acceleration measurement</b>	$\min(\Delta x)$	$-0.23 \pm 0.44$	$-2.07 \pm 1.33$	Yes
<b>CV: Variance of change in acceleration measurements</b>	$\frac{\sum (\Delta x - \mu)^2}{10}$	$0.05 \pm 0.21$	$1.56 \pm 1.75$	Yes
<b>CV: Maximum of absolute value of change in acceleration measurements</b>	$\max( \Delta x )$	$0.26 \pm 0.48$	$2.41 \pm 1.45$	Yes
<b>CV: Total sum of absolute values of change in acceleration measurements</b>	$\sum  \Delta x_i $	$0.66 \pm 1.15$	$6.96 \pm 4.78$	Yes