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1 **Lying behaviour of housed and outdoor-managed pregnant sheep**

2 **Manod Williams^{a*}, Chelsea N. Davis^a, Dewi Llyr Jones^{a,b}, Emma S. Davies^a, Penelope Vasina^a,**
3 **David Cutress^a, Michael T. Rose^{a,c}, Rhys Aled Jones^a, Hefin Wyn Williams^a**

4 ^aInstitute of Biological, Environmental and Rural Science, Aberystwyth University, Penglais Campus,
5 Ceredigion, SY23 3DA, United Kingdom

6 ^bColeg Cambria, Llysfasi, Ruthin Road, Ruthin, Denbighshire, LL15 2LB, United Kingdom

7 ^cTasmanian Institute of Agriculture, University of Tasmania, Sandy Bay, TAS 7005, Australia

8 *Corresponding author: Manod Williams. Institute of Biological, Environmental and Rural Science,
9 Aberystwyth University, Penglais Campus, Ceredigion, SY23 3DA, United Kingdom E-mail:
10 maw90@aber.ac.uk

11

ABSTRACT

12 Lying behaviour has been shown to be highly valuable in supporting the productivity and welfare of
13 cattle. The aim of this experiment was to investigate the effect of biological and physical factors on
14 the lying behaviour of sheep. Ninety-six Bluefaced Leicester x Welsh Mountain crossbred (Mule)
15 ewes managed to lamb indoors, and 80 Welsh Mountain (WM) ewes managed to lamb at grass were
16 used for the study. Acceleration values were collected for the two flocks from accelerometers fitted
17 vertically to the outside of the rear right leg and set to record at 1-min intervals for at least 14 d prior
18 to parturition. Ewes were simultaneously recorded using video equipment to identify lambing and to
19 verify predictions of lying (total lying time, mean lying bout duration and total number of lying bouts)
20 using data collected from 10 randomly selected ewes from the indoor flock on day -10 prior to
21 lambing. Linear regression was used to evaluate predicted behaviours with video footage. Predictions
22 of total lying time ($R^2 \geq 0.99$; $P > 0.05$ for slope = 1, intercept = 0), mean lying bout duration ($R^2 \geq$
23 0.99 ; $P > 0.05$ for slope = 1, intercept = 0) and total number of lying bouts ($R^2 \geq 0.98$; $P > 0.05$ for
24 slope = 1, intercept = 0) were strongly associated with video footage ($P < 0.001$) demonstrating that a
25 1-min sampling interval provides reliable estimates of ewe lying behaviours. Measures of lying (mean
26 daily lying time, mean lying bout duration and mean daily lying bouts) were calculated for all ewes
27 using averages taken across days -10, -9 and -8 prior to lambing. Linear regression was used to test
28 for effects of independent variables (pregnancy scan result (single- or twin-bearing), ewe age, ewe
29 BCS, lambing ease, lamb sex and lamb birth weight) on each measure of lying. Significant
30 associations ($P < 0.05$) were found between measures of lying and pregnancy scan result, ewe age,
31 sex of singleton lambs and twin birth weight for housed, Mule ewes. Only ewe age and twin birth
32 weight were significantly associated ($P < 0.05$) with measures of lying for WM ewes managed at
33 grass. This information could help guide further research on sheep behaviour for management
34 purposes (e.g., to optimise stocking densities and welfare for pregnant ewes). Further work should
35 also consider evaluating measures of lying as proxies for imminent parturition.

36 **Keywords**

37 **Sheep; Behaviour; Accelerometers; Pregnant; Lying behaviour; Lambing**

38

1. INTRODUCTION

39 The use of precision sensors to monitor the behaviour and performance of livestock has been shown
40 to be highly valuable, and significant research and development have been undertaken in support of
41 the management of cattle (Caja et al., 2016) and other intensively managed animals (Benjamin and
42 Yik, 2019; Li et al., 2020). Discrete, on-animal sensors are now providing previously unattainable
43 information, allowing for a better understanding of livestock behaviour for managing comfort (Molina
44 et al., 2020) and production disorders (Wagner et al., 2020) using sensors such as pedometers
45 (Edwards and Tozer, 2004) and accelerometers (Reiter et al., 2018). Further development of
46 integrated systems on farms will provide farmers with the information necessary to make management
47 decision at the level of the individual animal as well as at flock or herd level. Some sectors of the
48 livestock industry have seen a greater emphasis on the development of precision sensors and systems,
49 in-part because of the economic necessity and incentive to do so such as in the dairy industry (Rutten
50 et al., 2013). For example, the fertility management of cattle has developed greatly in recent years
51 with information such as feeding duration and activity used to support the optimum time for artificial
52 insemination (Mottram, 2016).

53 More recently, it has been demonstrated that the management of sheep could also be
54 supported by on-animal sensor technology. For example, accelerometers were used to measure the
55 activity of growing lambs showing promise for the early detection of behavioural changes associated
56 with parasitism (Ikurior et al., 2020). Research has also been undertaken to assess the feasibility of
57 recording other measures from sheep including attributes of movement for identifying gait anomalies
58 associated with lameness (Barwick et al., 2018), feeding behaviour (Giovanetti et al., 2017) and also
59 parturition (Fogarty et al., 2020). However, few studies have assessed the behaviour of sheep in
60 commercial settings. This will be needed to effectively differentiate optimal from suboptimal
61 performance. Lambing represents an important period in the production cycle for ewe comfort and
62 welfare but relatively little is known about the behaviour of pregnant sheep. Often, shepherds are in
63 increased contact with sheep during this time and this presents an opportunity to test the feasibility of
64 using well-established activity monitoring techniques. Lying behaviour has been shown to be a highly
65 valuable metric of behaviour in other species (Jensen, 2012; Blackie et al., 2011) and can be measured

66 and monitored using accelerometers. These methods require low computational power and data
67 processing and have been shown to be highly valuable in identifying indicators to support the
68 management of other livestock (Ito et al., 2009). To date, no exploratory analyses on the lying
69 behaviour of pregnant sheep have been undertaken using accelerometers. This information could be
70 useful to better understand the behaviour of sheep particularly during times of increased stress (e.g.,
71 lambing) and provide information on the degree of variability within measures of lying that might be
72 present in a flock.

73 The aim of this experiment was to investigate the effect of biological and physical factors on
74 the lying behaviour of pregnant sheep. The objectives were 1.) to validate the use of leg-mounted
75 accelerometers for measures of lying behaviour 2.) explore whether commonly measured biological
76 and physical attributes of sheep around the time of lambing contribute to variability in measures of
77 lying behaviour. To achieve this, both indoor- and outdoor-lambing flocks were studied, representing
78 common UK sheep production systems. We hypothesised that variation in economically important
79 attributes of sheep (e.g., age, BCS and lambing ease), would partly explain variations in lying
80 behaviour during the final trimester of pregnancy.

81

2. MATERIALS & METHODS

82 The study was approved by Aberystwyth University Animal Welfare and Ethical Review Board on
83 18th December 2018.

84 *2.1. Study farms*

85 Data were collected at two different farms representing lowland (Farm A; Gogerddan farm,
86 Aberystwyth University, Wales) and upland (Farm B; Llysfasi Farm, Coleg Cambria, Wales)
87 commercial lamb-producing enterprises between February and May 2019. Farm A lies approximately
88 40 m above sea level and is situated 6 km north-west of Aberystwyth, Ceredigion, Wales. The farm
89 comprises approximately 1,000 ewes of predominantly Welsh Mule-type sheep (Bluefaced Leicester
90 x Welsh Mountain (WM) crossbred ewes), with a small number of both Beulah and pure-bred Texel
91 ewes that are managed at grass throughout the year and housed in January to lamb between February
92 and March. Lambs are finished at grass. Farm B ranges between 200-300 m above sea level and is
93 situated 6 km south of Ruthin, Denbighshire, Wales and includes approximately 1,000 WM ewes and
94 160 Welsh crossbred ewes. The flock is managed at grass throughout the year with ewes lambing
95 between April and May. After weaning, lambs are finished at grass with a proportion finished on
96 silage and concentrate feed.

97 *2.2. General ewe management*

98 The first experiment took place at Farm A. Following an autumn mating period, ewes were
99 pregnancy scanned on the 8th and 15th January 2019 and housed in two barns with capacity for
100 approximately 600 ewes. Ewes were penned according to their pregnancy status, with single, twin and
101 triplet-bearing ewes managed separately in straw-bedded pens measuring 8.8 m x 6.1 m. On average,
102 each pen contained approximately 40 ewes at any given point. Ewes had *ad-libitum* access to water
103 and a complete ration comprising of grass silage and a protein blend dispensed twice per day at 0800
104 and 1600 throughout their third trimester of pregnancy. Upon lambing, ewes were moved with their
105 offspring to an individual 1.5 m x 1.5 m pen situated around the inner perimeter of each barn. Both
106 ewes and lambs remained in these single pens for at least 24 h before being moved out to pasture or to
107 a separate larger pen. The second experiment took place at Farm B. All ewes were pregnancy scanned

108 on the 14th February 2019 and only those selected for the experiment were brought-in to in-bye fields
109 surrounding the farm buildings on the 9th March 2019 prior to lambing. For the purpose of the
110 experiment, both single and twin-bearing ewes were lambed as mixed groups in two fields (field A;
111 0.66 ha and field B; 0.87 ha) close to the farm buildings. Ewes were managed at grass throughout the
112 lambing period, had free access to water and were supplemented with *ad-libitum* access to a glucose
113 lick.

114 **2.3. Ewe selection and data collection**

115 **2.3.1. Farm A - indoor lambing**

116 Of the 600 Mule ewes that were initially due to lamb at Farm A, a group of 46 single-bearing
117 and 52 twin-bearing ewes were selected and entered the experiment on the 25th and 26th February
118 2019. The age of each ewe was recorded (Cocquyt et al., 2005), and its body condition score (BCS =
119 1-5; Russel, 1984) and locomotion score (locomotion score 0-3; Angell et al., 2015) recorded by a
120 single observer. All study ewes had a locomotion score of 0. Ewes were clearly spray marked on each
121 side with a unique number for identification purposes and randomly allocated to one of six pens
122 allowing for 1.3 m² per ewe. To record the lying behaviour of the experimental ewes, HOBO Pendant
123 G accelerometers (Onset Computer Corporation, Bourne, MA) were fitted to the outside of the right-
124 hind leg of each ewe according to a standard operating procedure (UBC Animal Welfare Program,
125 2013). The accelerometers were fitted vertically, such that the X-axis was pointing upward and the Z-
126 axis pointing left towards the midplane of the ewe. Accelerometers were configured to sample at 1-
127 min intervals. This sampling interval was selected as it has been previously used to record the lying
128 behaviour of dairy goats (Zobel et al., 2015) and is well-established for use in monitoring the lying
129 behaviour of cattle (Ledgerwood et al., 2010). This sampling interval also allowed for 14 d of
130 continuous data recording which meant that ewes could remain undisturbed other than for daily
131 management. Once accelerometers were fitted, each ewe was placed back into its allocated pen where
132 it remained until it gave birth. In order to visually verify predicted behaviours and the time of
133 lambing, cameras (5MP PoE Security Camera System, Reolink) were fitted to the end of each pen
134 containing focal ewes and were set to record throughout the entire experimental period. During the

135 night, the lights in the building remained on for management purposes. Upon lambing, ewes were
136 moved to individual pens and their accelerometer removed. At this point, measures were recorded for
137 each lamb, including lambing difficulty (0 = no assistance, 1 = slight assistance, 2 = severe assistance,
138 3 = veterinary assistance) birth weight (kg) and sex. For ewes that had not given birth within the
139 initial 14 d observation period ($n = 48$), the original accelerometer was removed and replaced with a
140 second accelerometer which remained in place until the ewe had given birth. Upon removal, data were
141 downloaded from each accelerometer and saved in a spreadsheet program. Other than for specific
142 experimental procedures and data capture, all ewes were managed and monitored 24 h/d by farm
143 shepherds. Data collection was complete by 22nd March 2019 at Farm A. Three single-bearing ewes
144 did not lamb during the trial leaving only pre-lambing variables for testing for these ewes. Behaviour
145 data for two twin-bearing ewes were not available due to the failure of accelerometers and a further
146 two did not give birth during the trial. This left a total of 46 single-bearing ewes ($n = 43$ for all
147 variables) and 50 twin-bearing ewes ($n = 48$ for all variables) available for analysis.

148 **2.3.2. Farm B - outdoor lambing**

149 Of the ewes brought-in to in-bye fields at Farm B on the 9th March 2019, 44 were single-
150 bearing and 45 were twin-bearing WM ewes. At this point, the age of all ewes was determined, and
151 their body condition and locomotion scores recorded as described previously. For locomotion, three
152 ewes received a score of 1 and were treated for scald by farm staff. All other ewes were scored as 0.
153 Ewes were also fitted with an accelerometer and equally split between fields A (mean over
154 experiment = 40 sheep) and B (mean over experiment = 33 sheep). Six cameras (5MP PoE Security
155 Camera System, Reolink) were fitted around the boundary of field A to record as much information as
156 possible such as the time of lambing which may have been missed by the shepherd. Once ewes in
157 field A had given birth, they were replaced with ewes from field B in order to maximise the number
158 of ewes captured on video giving birth. Ewes were regularly monitored by a shepherd at least 3-times
159 daily between 06:30 h-08:30 h, 11:30 h-13:30 h and 16:00 h-18:00 h. All observations were made
160 from the boundary of the field and closer inspection was only undertaken when necessary. Shortly
161 after lambing, measures were recorded for each lamb as described for Farm A and if required, video

162 footage was used to verify the time of birth. At this point, accelerometers were removed, and data
163 downloaded. Accelerometers were replaced on ewes that had not given birth ($n = 59$) within the initial
164 14 d observation period before being returned to their respective field. Only seven ewes required any
165 level of birthing assistance in the flock monitored at Farm B, so this factor was not included in this
166 analysis. Data collection was complete by 1st May 2019 at Farm B. Data for three single-bearing ewes
167 were missing due to a fault with the accelerometers. One other single-bearing ewe did not lamb during
168 the trial and so analysis of post-birth data was not possible for this ewe. For twin-bearing ewes, six
169 accelerometers failed to function. This left a total of 41 single-bearing ewes ($n = 40$ for all variables)
170 and 39 twin-bearing ewes ($n = 39$ for all variables) available for analysis.

171 **2.4. Data processing**

172 Accelerometer data (g -force values) for each ewe were processed using R statistical software
173 (R Core Team, 2019) in a program adapted from that developed by UBC Animal Welfare Program
174 (UBC, 2013) based on the method of Ledgerwood et al. (2010). Guidance provided by Zobel et al.
175 (2015) for accelerometer cut-off values was used to determine whether the ewe was in a lying (or
176 standing) position and these values were incorporated into the program. Lying laterality was not
177 explored in this experiment as further work is required to determine suitable accelerometer thresholds
178 for sheep. Behaviours computed from the raw accelerometer data included lying time (min/d), lying
179 bouts (n/d) and lying bout duration (min/bout) using the X-axis data only. These behaviours were
180 calculated for each ewe, for each day that the accelerometer remained in place. It has been shown
181 previously that at least 3 d of behaviour data are required to obtain a reliable estimate of the behaviour
182 of cattle (Ito et al., 2009) and a similar method has been applied to dairy goats (Zobel et al., 2015). In
183 order to reliably estimate the behaviours of each ewe, the computed values for measures of lying were
184 standardised by averaging three days of data in the 10-d period prior to the day of lambing. These
185 were days -10, -9 and -8 prior to lambing for each ewe as it was hypothesised that the behaviour of
186 ewes may be influenced by the onset of lambing (behaviour change within 24 hrs of birth) (Echeverri
187 et al., 1992; Fogarty et al., 2020). This procedure was repeated for all ewes at both farms. For ewes
188 that had not given birth in the initial 14 d observation period (Farm A = 48 sheep; Farm B = 59

189 sheep), two spreadsheets were saved, and the second spreadsheet processed for measures of lying for
190 this experiment. For all ewes, the first day of accelerometer data was ignored, as were data recorded
191 on the day of accelerometer changeover (if necessary). This was to allow for a 24 h settling-in period.
192 A total of 10 ewes ($n = 5$ single-bearing, $n = 5$ twin-bearing) from Farm A were randomly selected to
193 verify lying behaviours with recorded camera footage (24 h for each ewe).

194 **2.5. Statistical analysis**

195 To validate the accuracy of the accelerometer measurements, estimates of total lying time,
196 total number of lying bouts and mean bout duration were compared with video footage taken on day -
197 10 before lambing for 10 randomly selected ewes at Farm A (24 hrs each for 5 single- and 5 twin-
198 bearing ewes) using linear regression. Transitions between lying and standing were recorded on a per
199 second basis and rounded to the nearest minute in a spreadsheet program for analysis with predicted
200 behaviours. Regression slopes and intercepts were evaluated to see whether they differed significantly
201 ($P \leq 0.05$) from 1 and 0 respectively.

202 Two of the three measures of lying were not normally distributed; therefore, median values
203 were used to assess all measures (lying time (h/d), lying bouts (n/d) and lying bout duration
204 (min/bout)) separately for both farms. The outcome variables “lying bouts per day” and “lying bout
205 duration” were log transformed to achieve data normality. Single variables were then tested for their
206 association with the 3 measures of lying using simple linear regression separately for both farms with
207 ewe within each farm as the observational unit. For Farm A, empty models were first tested to
208 estimate the random effect of pen (1-6), but the variation explained by pen was found to be non-
209 significant ($P > 0.05$). Single variables associated with ewes at both farms included pregnancy scan
210 result (single or twin), age ($1 \geq 5$) and BCS (1-5). Variables associated with lambs at both farms
211 included lamb sex and lamb birth weight (kg). Only seven ewes required birthing assistance at Farm B
212 so lambing ease (0-3) was not analysed for this farm. No ewes at Farm A scored 3 for lambing
213 assistance. The statistical significance of a relationship was declared when the probability of the
214 regression slope differing from zero was ≤ 0.05 . All statistical analyses were undertaken in R (R Core
215 Team, 2019).

216

3. RESULTS

217 *3.1. Associations between accelerometer predictions and video recordings*

218 Results for linear regression models between predicted measures of lying and those verified by video
219 recordings for 10 sheep at Farm A are shown in Table 1. A strong linear relationship was found for all
220 three measures of lying ($P < 0.001$) with coefficients of determination ≥ 0.99 , 0.99 and 0.98 for total
221 lying time (min/d), mean lying bout duration (min/bout) and total number of lying bouts (n/d)
222 respectively. With the accelerometer set to sample at 1-min intervals, accurate estimates of lying
223 behaviours were obtained with each regression slope and intercept not differing significantly from 1
224 and 0 respectively ($P > 0.05$).

225 *3.2. Measures of lying behaviour of housed and outdoor managed ewes*

226 Ewes ($n = 96$) studied at Farm A (Figure 1A) spent a median duration of 13.1 h/d lying down (25th –
227 75th percentile = 11.9 – 14.3 h/d), had a lying bout frequency of 26.8 bouts/d (25th – 75th percentile =
228 23.3 – 31.1 bouts/d) and a median bout duration of 29.5 min/bout (25th – 75th percentile = 25.2 – 33.6
229 min/bout). Ewes ($n = 80$) at Farm B (Figure 1B) spent a median duration of 11.7 h/d lying down (25th
230 – 75th percentile = 10.3 – 12.9 h/d), had a lying bout frequency of 19 bouts/d (25th – 75th percentile =
231 15 – 23.8 bouts/d) and a median bout duration of 35.9 min/bout (25th – 75th percentile = 30.8 – 45.4
232 bouts/d).

233 Univariate results for Farm A (Table 2) found that pregnancy scan result (foetal numbers) was
234 significantly associated ($P = 0.02$) with the daily duration of lying of ewes. On average, twin-bearing
235 ewes lay down 48.51 min/d longer than single-bearing ewes. However, no significant differences
236 were found for frequency of lying bouts ($P = 0.60$) or lying bout duration ($P = 0.46$) between the
237 groups.

238 There was no overall effect of age ($P = 0.15$) on the daily lying duration of ewes, but age was
239 significantly associated with the number of daily lying bouts ($P = 0.01$) and the duration of each bout
240 ($P = 0.04$). The duration of lying bouts for three-year old ewes was shorter, and the number of daily
241 bouts was higher in this age group compared to the reference level (1-year-old ewes).

242 A significant association ($P = 0.03$) was found between the sex of singleton lambs and the
243 daily lying time of ewes. Ewes carrying male lambs lay down for a shorter (-67.07 min) daily
244 duration. No associations were found between the sex of singletons and the other two measures of
245 lying. For twin-bearing ewes, no associations were found between the sex of lambs (male, female or
246 mixed-sexed groups) and any of the three measures of lying. Similarly, no associations were found
247 between the birth weight of singletons and any of the three measures of lying. However, of the twin-
248 bearing ewes, as twin birth weight increased there was a highly significant reduction ($P < 0.001$) in
249 the daily duration of lying (-43.07 min/d). This effect could not be accounted for by significant
250 changes to lying bout duration ($P = 0.54$) or lying bout frequency ($P = 0.22$). No other significant
251 associations were found between any of the other factors measured at Farm A and the three measures
252 of lying.

253 In contrast to ewes managed indoors at Farm A, no significant effect of pregnancy scan result
254 was found for the three measures of lying behaviour for the ewes managed at the outdoor system at
255 Farm B (Table 3). Furthermore, only the frequency of lying bouts was found to be associated with
256 ewe age ($P = 0.02$). As with Farm A, no associations were found between ewe BCS and measures of
257 lying at Farm B.

258 In contrast to the Mule ewes at Farm A, no significant effect was found for the sex of
259 singleton lambs on the three measures of lying, but similarly, no effect of the sex of twin lambs was
260 found. Effects of lamb birth weight on measures of lying were only found for twin-bearing ewes at
261 Farm B. Increasing twin birth weight was associated with shorter lying bouts ($P = 0.03$) and a higher
262 daily frequency of lying bouts ($P < 0.01$). Despite these associations, no significant relationship was
263 found between twin birth weight and daily lying duration for WM ewes at Farm B.

264

4. DISCUSSION

265 The HOB0 accelerometer showed accurate estimates of lying behaviour when verified against video
266 recordings of housed sheep. A 1-min sampling interval was sufficient in recognising 96% of lying
267 events in the 10 sheep used for verification at Farm A. Across the 10-test sheep, the average (\pm SD)
268 number of missed lying bouts was 1.5 ± 1.1 . All missed lying bouts were those that from the video
269 footage had a duration of between 30-59 s, which upon rounding were logged as a lying bout.
270 However, all lying bouts lasting < 1 -minute were occasions where focal sheep were displaced, or a
271 disturbance had occurred where farm staff were operating. All lying events lasting ≥ 1 -min were
272 identified by the accelerometer in the verification group. Shortening the sampling interval to 30 s
273 would probably capture lying events lasting < 1 -minute but this would also have the effect of halving
274 the number of days that data can be logged for. With this, we believe that a 1-min sampling interval,
275 providing 14 d of continuous data capture is sufficient and provides highly accurate estimations of
276 measures of lying of sheep as has been shown in studies of cattle (Ledgerwood et al., 2010;
277 Mattachini et al., 2013). Lying-side preference (laterality) has been found to vary considerably with
278 cattle and affected by factors such as pregnancy status and discomfort (Tucker et al., 2009). Laterality
279 was not explored in the current study. More work is required in examining the importance of lying
280 laterality in the study of sheep behaviour as has been done with cattle (Gibbons et al., 2012; Miller-
281 Cushon et al., 2019) and goats (Zobel et al., 2015). If found to be useful, work will be needed to
282 accurately estimate measures of lying laterality in sheep, using appropriate thresholds from
283 accelerometer data.

284 This is the first time that measures of lying behaviour for both housed and outdoor-managed
285 pregnant sheep have been recorded using this method. The results of the exploratory analyses provide
286 an objective insight into the daily lying times of pregnant ewes and show that significant variation
287 exists between individuals for measures of daily lying behaviour in each of the studied flocks. The
288 median daily lying duration, lying bout frequency and bout duration for housed sheep was 13.1 h/d,
289 26.8 bouts/d and 29.5 min/bout respectively. For the outdoor flock these values were 11.7 h/d, 19
290 bouts/d and 35.9 min/bout respectively. In a previous study, Arnold (1984) used direct visual
291 observations to measure the lying behaviour of sheep co-grazing with cattle and horses in a

292 Mediterranean environment. The average daily lying duration of sheep was 11.6 h per day which
293 broadly coincides with the results of the current study, particularly for the WM ewes at grass. Others
294 have assessed lying time as a proportion of total time using visual observations. A mean daily lying
295 proportion of 66% was found in a study examining the effect of pen size (mean = 0.75 m² per ewe) on
296 lying behaviour of pregnant, Norwegian Dala sheep (Bøe et al., 2006) and a lying proportion of 70%
297 in a study allowing for 1.5 m² per pregnant ewe (Jørgensen et al., 2009). In the current study, Mule
298 ewes at Farm A spent 55% of their time lying (~1.3 m² per ewe) whereas WM ewes at Farm B spent
299 49% of their time lying which substantially differs from the studies noted. A low daily lying
300 proportion might have been expected for the housed flock at Farm A given the high level of staff
301 interaction and that lying space is more limited compared to when ewes are at grass. However, these
302 differences may also be explained in part by breed.

303 At Farm A, approximately 1.3 m² was available for each ewe which is within the guidelines
304 required for lowland, pregnant ewes (DEFRA, 2003). Little information is available on the expected
305 resting times of ewes in both housed and outdoor conditions, but some exploratory work has been
306 undertaken to assess the behaviour of pregnant ewes in relation to the amount floor space available in
307 housed conditions (Averós et al., 2014). It was found that ewes given a space allowance of 1 m²/ewe
308 travelled shorter distances but had greater levels of activity compared to ewes provided with either 2
309 or 3 m²/ewe. Although the lying bout duration of sheep at Farm B was longer than those of the housed
310 sheep, they spent less time lying each day and had fewer daily lying bouts compared to the housed
311 flock. These sheep may have spent more of their time foraging throughout the paddocks and
312 responding to a greater variety of stimuli.

313 Some of the measured variables were shown to be significantly associated with measures of
314 lying time in both systems. In the current study, housed sheep carrying twin-lambs had a greater daily
315 lying duration compared to single-bearing ewes, but this was not found for the ewes managed at grass.
316 This may have been linked to the combined weight of the developing foetuses. The average (\pm SD)
317 combined twin birth weight of lambs born to Mule and WM ewes was 9.55 kg (\pm 1.26) and 7.34 kg (\pm
318 1.73) respectively. Proportionally however, the birth weight of single lambs relative to the combined
319 weight of twin lambs was similar (65% and 64% for Mules and WM respectively). A better

320 comparison would be to assess birth weights with respect to maternal weights as has been undertaken
321 previously (Gardner et al., 2007), but these data were not available. It was also shown in that study
322 that the proportional increase in litter size relative to ewe weight was greater in Mules compared to
323 WM ewes, but it is also reported that hill breeds carry a significantly heavier litter proportional to
324 their own body weight (Dwyer and Lawrence, 2005). Both breed (e.g., ewe survival strategy) and
325 managerial factors (displacements and interventions by staff) may have contributed to the differences
326 seen between systems for daily lying time. In the housed system, although the lying time of twin-
327 bearing ewes was not explained by significant changes to bout duration or the number of daily bouts,
328 these insignificant yet marginally higher figures for twin-bearing ewes likely led to higher lying
329 times. Over the course of 24 hrs, the lying time accrued amounted to significantly higher levels
330 compared to the single-bearing ewes. One hypothesis for this finding is that when sheep are managed
331 at higher densities (e.g., housed) and in close proximity, they may be more reactive to one another
332 especially when disturbed by factors external to their pen environment e.g., staff on foot or feed
333 wagon entering. This behaviour might be influenced by the inability of some to immediately see the
334 disturbance which may be different to the field environment where sheep can react more
335 independently (Sibbald et al., 2009). Anecdotally, the footage for the verification study demonstrated
336 just how receptive the housed ewes were to human movement and intervention, frequently moving as
337 entire groups in response to various stimuli.

338 Effects of age on measures of lying were found in both flocks although the relationships were
339 different. In the WM flock, only the frequency of lying bouts was associated with age with more bouts
340 undertaken in older ewes compared to younger ewes. In the housed ewes, both lying bout duration
341 and lying bout frequency were associated with age. The duration of lying bouts for three-year old
342 ewes were shorter with a greater number of daily lying bouts compared to 1-year old ewes. Parity
343 effects on lamb birth weight, litter weight and placenta weight have been reported previously with
344 significant increases in each with parities 1-3 (Dwyer et al., 2005). The authors also reported that
345 although lamb birth weights and litter weights were greater for Suffolk ewes compared to Blackface
346 ewes, litter weight expressed as a percentage of maternal weight was significantly greater for
347 Blackface ewes. Breed and environment may play a role in the behaviour of older ewes but given the

348 relatively few numbers available for inclusion in the higher age categories, further work would be
349 needed to fully evaluate these findings.

350 Interestingly, and for the housed sheep only, ewes carrying a male singleton lamb had
351 significantly lower daily lying times compared to ewes carrying female singleton lambs. Again, this
352 effect could not be fully explained by significant changes to the other two measures of lying and may
353 again be a cumulative effect of marginal reductions in lying bout duration as well as the number of
354 bouts. The average birth weight (\pm SD) of male and female singletons was 6.54 kg (\pm 0.99) and 5.98
355 kg (\pm 0.97) respectively and this may have explained the differences recorded in ewe lying time. It is
356 known that bearing male lambs can lead to increased labour duration and birthing difficulty (Dwyer,
357 2003) which can ultimately affect lamb survival. However, to our knowledge, little is known about
358 the prepartum behaviour of the ewe with respect to the sex of the lamb. This effect was not found for
359 twin-bearing ewes and it may be that for these ewes, the combined foetal weight is a more important
360 factor in defining measures of lying compared to lamb sex.

361 In both flocks, effects of increasing combined twin birth weights were found, but no effect of
362 singleton birth weight was found on any measure of lying. For housed ewes, daily lying times
363 decreased significantly with higher combined twin birth weights but neither lying bout duration or the
364 frequency of lying bouts were significantly affected. This may again relate to group behaviour in a
365 housed environment. Ewes with heavier twin-foetuses may only be losing marginal lying time per
366 lying bout compared to ewes with lighter twin-foetuses resulting in an overall significant reduction in
367 lying time with increasing twin-birth weight. One explanation may be that heavier twin foetuses lead
368 to greater lying discomfort during the final stages of pregnancy leading to increased time spent
369 standing. There are advantages to increased litter weights such as lamb survival, and other studies
370 have measured pre- and postnatal behaviours of several breeds and their associations with lamb
371 survival (Lynch et al., 1980; Rachlow and Bowyer, 1998) as well as biological factors (e.g., placental
372 efficiency) that may favour increased litter weight in hill breeds (Dwyer et al., 2003). For ewes at
373 grass, although there was no significant relationship between twin birth weight and daily lying time,
374 the duration of lying bouts decreased and the number of daily lying bouts increased significantly as

375 twin birth weight increased. This could again be a coping strategy for ewes with heavier twin
376 foetuses.

377 For housed ewes at Farm A, lambing ease was assessed, and it is perhaps unsurprising that
378 there were no significant associations between any of the three measures of lying and each level
379 within this factor. Measures of lying time were assessed more than a week prior to lambing and at this
380 point at least, no differences in lying behaviours were detected that may be associated with difficult
381 parturition. It is likely that assessments would be required closer to the day of parturition and it would
382 be worthwhile to explore this as indicators of birthing difficulty would be useful for shepherds for
383 effective time management during this busy period in both housed and extensive systems.

384 In this work, measurement days were standardised (days -10, -9 and -8 prepartum) for
385 comparison between individuals and it may be the case that the associations found could change again
386 with proximity to birth (e.g., postural changes). This work could also be extended to other flocks to
387 further evaluate these predictions. It is also important to note that variables such as locomotion score
388 were not explored which could impact lying behaviour as has been shown with cattle (Thomsen et al.,
389 2012; Weigele et al., 2018). Furthermore, exploring the impact of stocking density and breed on ewe
390 behaviour would also be useful. Further studies should also seek to identify whether one or more of
391 these measures of lying could be used as alternatives to more computationally intensive strategies to
392 identify parturition or ill health.

393

5. CONCLUSION

394 This is the first study that has explored the lying behaviour of housed and outdoor-managed pregnant
395 sheep using leg-mounted accelerometers. HOB0 accelerometers accurately recorded measures of
396 lying time at a 1-min sampling interval showing wide variation between individual sheep. This
397 method can be recommended for recording flock lying behaviour over short durations. For Mule
398 sheep managed indoors, significant associations were found between measures of lying and pregnancy
399 scan result (single or twins carried), age of ewe, lamb sex (single) and the birth weight of twin lambs.
400 For WM sheep managed at grass, associations were only found for ewe age and twin lamb birth
401 weight. Further studies should seek to identify any further implications of these findings such as the
402 impact of stocking density on lying behaviour given pregnancy status. In addition, work should be
403 undertaken to assess whether simple measures of lying can be used to evaluate health status or to
404 predict imminent lambing which would be particularly useful for flock managers in extensive
405 systems.

406

DECLARATION OF COMPETING INTEREST

407 The authors declare no competing interest.

408

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419

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Behaviour	Intercept	SE	95% CI	<i>P</i> -value	Slope	SE	95% CI	<i>P</i> -value	R ²
Total lying (min/d)	0.23	8.39	-19.11 – 19.58	0.98	0.99	0.01	0.97 – 1.02	<0.001	0.99
Mean lying bout duration (min/bout)	0.005	0.17	-0.39 – 0.40	0.98	1	0.001	0.98 – 1.02	<0.001	0.99
Total lying bouts (n/d)	0.58	1.92	-3.86 – 5.01	0.77	1.03	0.06	0.9 – 1.16	<0.001	0.98

550 Table 1. Parameters of linear regression models for predicted measures of lying by HOB0
551 accelerometers and behaviours recorded by video for 10 housed, Mule sheep at Farm A

Table 2. Results of simple linear regression models for variables hypothesised to be associated with measures of lying time of pregnant, housed Mule ewes at Farm A

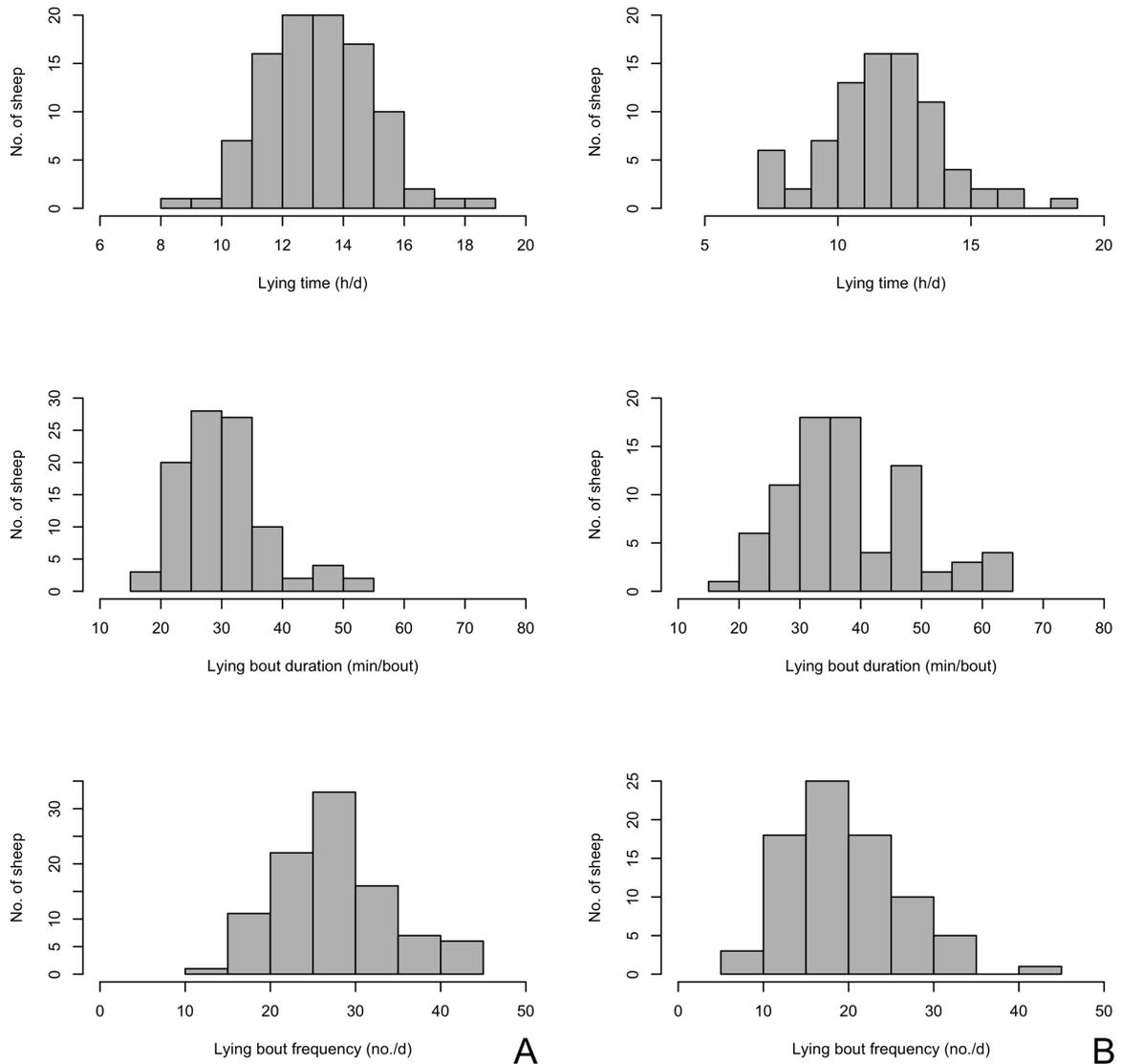
Variable	Level	Number of sheep	Daily lying duration (min/d)			Lying bout duration (log min/bout)			Frequency of lying bouts (log bouts/d)		
			Coefficient	95% CI	<i>P</i> -value	Coefficient	95 % CI	<i>P</i> -value	Coefficient	95 % CI	<i>P</i> -value
Pregnancy scan result	Single	46	Reference	-	0.02	Reference	-	0.46	Reference	-	0.60
	Twin	50	48.51	7.22 – 89.81		0.04	-0.06 – 0.13		0.03	-0.07 – 0.13	
Age	1	9	Reference	-	0.15	Reference	-	0.04	Reference	-	0.01
	2	21	-9.87	-91.03 – 71.29		-0.13	-0.31 – 0.05		0.12	-0.07 – 0.30	
	3	32	-40.30	-117.16 – 36.56		-0.21	-0.38 – -0.03		0.15	-0.02 – 0.33	
	4	21	-38.63	-119.79 – 42.53		-0.18	-0.36 – 0.01		0.13	-0.06 – 0.31	
	≥5	13	-96.00	-184.34 – -7.67		-0.01	-0.21 – 0.19		-0.11	-0.31 – 0.09	
BCS	≤2	10	Reference	-	0.54	Reference	-	0.90	Reference	-	0.67
	2.5	34	42.97	-31.77 – 117.70		-0.01	-0.19 – 0.16		0.07	-0.11 – 0.25	
	3	39	43.76	-29.88 – 117.40		-0.05	-0.22 – 0.12		0.11	-0.07 – 0.28	
	≥3.5	13	63.54	-23.85 – 150.92		-0.01	-0.21 – 0.19		0.08	-0.12 – 0.29	
Lambing ease single	0	26	Reference	-	0.37	Reference	-	0.74	Reference	-	0.47
	1	11	-51.15	-123.95 – 21.65		0.04	-0.15 – 0.23		-0.10	-0.29 – 0.09	
	2	7	-19.78	-105.97 – 66.40		-0.06	-0.29 – 0.16		0.03	-0.19 – 0.26	
Lambing ease twin (1)	0	31	Reference	-	0.71	Reference	-	0.96	Reference	-	0.79
	1	12	-28.02	-98.94 – 42.90		0.02	-0.14 – 0.17		-0.05	-0.21 – 0.10	
	2	5	4.92	-95.84 – 105.76		0.02	-0.20 – 0.24		-0.01	-0.23 – 0.21	
Lambing ease twin (2)	0	27	Reference	-	0.65	Reference	-	0.80	Reference	-	0.88
	1	16	24.73	-40.81 – 90.26		0.04	-0.10 – 0.19		-0.02	-0.16 – 0.13	
	2	5	-17.87	-119.40 – 83.65		0.04	-0.18 – 0.26		-0.05	-0.28 – 0.17	
Lamb sex - single	Female	25	Reference	-	0.03	Reference	-	0.44	Reference	-	0.70
	Male	18	-67.07	-127.47 – -6.68		-0.06	-0.21 – 0.10		-0.03	-0.18 – 0.12	
Lamb sex - twins	Female	15	Reference	-	0.48	Reference	-	0.21	Reference	-	0.60

	Male	11	32.89	-51.07 - 116.86		0.12	-0.05 - 0.29		-0.08	-0.27 - 0.10	
	Mixed	21	-14.81	-86.32 - 56.70		-0.02	-0.16 - 0.13		-0.01	-0.16 - 0.15	
Birth weight single	-	43	5.32	-26.33 - 36.97	0.74	-0.03	-0.10 - 0.05	0.50	0.03	-0.05 - 0.11	0.44
Birth weight twins	-	48	-43.07	-66.18 - -19.96	< 0.001	-0.02	-0.07 - 0.04	0.54	-0.03	-0.09 - 0.02	0.22

Variable	Level	Number of sheep	Daily lying duration (min/d)			Lying bout duration (log min/bout)			Frequency of lying bouts (log bouts/d)		
			Coefficient	95% CI	P-value	Coefficient	95% CI	P-value	Coefficient	95% CI	P-value
Pregnancy scan result	Single	41	Reference	-	0.42	Reference	-	0.13	Reference	-	0.43
	Twin	39	-23.02	-80.14 - 34.10		-0.09	-0.21 - 0.03		0.06	-0.08 - 0.20	
Age	2	21	Reference	-	0.44	Reference	-	0.12	Reference	-	0.02
	3	25	44.13	-30.77 - 119.04		-0.09	-0.25 - -0.06		0.16	-0.02 - 0.33	
	4	23	50.67	-27.22 - 128.56		-0.12	-0.28 - 0.04		0.21	0.02 - 0.39	
	5	11	68.62	-26.40 - 163.65		-0.24	-0.43 - -0.04		0.34	0.12 - 0.57	
BCS	2.5	9	Reference	-	0.28	Reference	-	0.99	Reference	-	0.84
	3	37	-77.75	-171.92 - 16.42		-0.01	-0.19 - 0.22		-0.14	-0.37 - 0.09	
	3.5	28	-42.99	-140.08 - 54.10		0.002	-0.21 - 0.21		-0.06	-0.30 - 0.18	
	4	6	-5.80	-139.34 - 127.74		-0.001	-0.29 - 0.29		-0.01	-0.34 - 0.32	
Lamb sex - single	Female	21	Reference	-	0.78	Reference	-	0.93	Reference	-	0.90
	Male	19	11.15	-69.43 - 91.73		0.01	-0.15 - 0.17		0.01	-0.20 - 0.22	

Lamb sex - twins	Female	10	Reference	-	0.56	Reference	-	0.36	Reference	-	0.17
	Male	10	-15.77	-138.99 – 107.46		-0.13	-0.40 – 0.13		0.11	-0.17 – 0.39	
	Mixed	19	-55.97	-164.64 – 52.70		0.03	-0.20 – 0.26		-0.12	-0.36 – 0.13	
Birth weight single	-	40	19.04	-26.09 – 64.17	0.40	-0.001	-0.09 – 0.09	0.91	0.03	-0.08 – 0.15	0.57
Birth weight twins	-	39	23.12	-4.62 – 50.85	0.10	-0.07	-0.12 – -0.01	0.03	0.10	0.04 – 0.16	< 0.01

554 Table 3. Results of simple linear regression models for variables hypothesised to be associated with measures of lying time of pregnant, Welsh Mountain
555 ewes managed at grass at Farm B
556



557
 558 **Figure 1.** Frequency distribution of daily lying time (h/d; top panels), lying bout duration (min/bout;
 559 middle panels) and lying bout frequency (n/d; bottom panels) for housed sheep at Farm A (A; $n = 96$)
 560 and sheep managed at grass at Farm B (B; $n = 80$). All measures of lying are averages taken on days -
 561 10, -9 and -8 parturium for each ewe. Daily lying time shown in h/d for clarity.