Potential role of biologgers to automate detection of lame ewes and lambs

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Abstract

Lameness is an important health, welfare and economic problem in sheep flocks and early treatment is key to controlling lameness. Biologging technology provides high-resolution, continuous data that offers a novel opportunity to detect lameness either directly or by identifying behavioural changes; either option would facilitate more rapid treatment of lame sheep than visual observation. Here, the role of biologging data to identify lame sheep through behavioural changes within and between sheep is investigated.

Accelerometers and proximity sensors were fitted to a flock of 50 Poll Dorset ewes rearing 32 single and 36 twin lambs, in Devon, UK in October 2019. Accelerometers were used to identify standing time and classify behaviour into four states for ewes (inactive, ruminating, grazing, walking) and three for lambs (inactive, sucking, moving). Principal components analysis reduced these behaviours to two components, 'feeding' and 'inactive' for ewes, and 'inactive' and 'feeding' for lambs. A visual locomotion score of each sheep was used each day to assess lameness. Complete records from sensors and locomotion observations were obtained for 513 days of ewe-activity and 720 days of lamb-activity (40 ewes, 26 single-raised and 28 twin-raised lambs). Linear mixed effects models were used to assess the effect of lameness adjusted for covariates age, litter size, social behaviour, environment and climate on standing time and the principal components.

Lame ewes stood less, spent less time grazing and were more inactive than non-lame ewes. Lame lambs also stood less and were more inactive than non-lame lambs. Lambs with severely lame dams were also more inactive than those with non-lame dams. In conclusion, it is possible to identify behavioural differences between lame and non-lame ewes and lambs which could help enable automated early warning of lameness and consequently early treatment of lameness, and improved sheep welfare.

1. Introduction

There is increasing interest in automated behaviour assessment for on-farm monitoring of animals using biologging sensors to provide early warning of health issues.

Commercially available behavioural monitoring products are available in the cattle industry, for example the MooMonitor+ (Dairymaster, Co. Kerry, Ireland) which detects both oestrous and sickness, via reductions in grazing time or increases in lying time, and IceTag (IceRobotics Ltd., Edinburgh, Scotland), which identifies lameness. Currently, there are no commercial biologging products for sheep, although behavioural changes for sick sheep, from increased parasite burden to exposure to mouldy feed, have been detected in experimental settings using biologgers for both ewes (Burgunder et al., 2018, Falzon et al., 2013, Gurule et al., 2022, Trieu et al., 2022) and lambs (Cronin et al., 2016, Ikurior et al., 2020, Högberg et al., 2021).

One of the most important concerns for the sheep industry globally is lameness. In England, most lameness is caused by the infectious diseases footrot and contagious ovine interdigital dermatitis with non-infectious granulomas and white line disease causing <5% of lameness (Kaler and Green, 2009, Lewis et al., 2021, Winter et al., 2015). All causes of lameness respond best to early treatment for the sheep itself and early treatment reduces the infectiousness and so reduces spread of infectious causes of lameness to flock mates (Green et al., 2007). Effective prompt treatment is also the most cost effective management practice (Wassink et al., 2010b, Winter and Green, 2017). Key to providing prompt treatment is early recognition of lameness. Automatic identification of lameness either directly, or through behavioural changes that indicate lameness, could enable rapid identification of lame sheep.

Animals have a “time-budget” each day and make choices about the utilisation of their time. Whilst there is some variability in behaviour between individuals in farm animals (Occhiuto et al., 2022, Thorup et al., 2015), there are also many common behaviours. Extensive work using accelerometers in experimental settings has identified grazing, ruminating, standing and walking behaviours in ewes (Alvarenga et al., 2016, Barwick et al., 2018, Price et al., 2022, Turner et al., 2022, Walton et al., 2018) and sucking, walking and inactivity in lambs (Högberg et al., 2020). Time-budgets are also influenced by environmental conditions such as rainfall (Champion et al., 1994), and heat (Bøe, 1990, Ozella et al., 2020).

Disease also affects behaviour, e.g. lambs with footrot lie more frequently for shorter duration than healthy lambs (Härdi-Landerer et al., 2017), and lame ewes with lambs spend less time in contact with non-family sheep than non-lame ewes (Lewis et al., 2022). To date, no studies have investigated the impact of lameness on time budgets in ewes or lambs. Understanding of how lameness impacts sheep daily time-budgets could help to farmers detect lameness promptly.

The aim of this study was to use the behavioural classifications from Price et al. (2022) in a small production setting, to quantify the effect of lameness on behaviour in ewes and lambs. Daily observations of locomotion were combined with continuous behavioural data from proximity sensors and accelerometers. Since sheep behaviour is driven by social interactions and the environment, these were included in models as important covariates.

2. Materials and Methods

2.1 Study location, sheep, pasture management, and climate

Ethical approval was granted by the University of Exeter (eCLESPsy000541). The study was carried out from 01/10/2019-15/10/2019 on a commercial farm with permanent grass leys in the Blackdown Hills, Devon, United Kingdom (latitude 50.9 degrees). All ewes and lambs in a flock of 50 pedigree Poll Dorset ewes with 68 lambs were used. Ewes lambed from mid-September outdoors and were brought in for 24 hours after parturition, then turned out to a single new field as ewes with lambs. The flock was kept as one for the entire study. By 01/10/2019, 50 ewes had lambed and the study began. Farm records for each animal in the flock included pedigree information, date of birth, sex and litter size. These are summarised in Table 1.

Poll Dorset ewes typically weigh 70-90kg and lambs are typically around 5kg at birth. Poll Dorsets have strong aseasonal reproductive capability, and the breeding cycle on the study farm (described more fully in Ozella et al., 2020) was typical for Poll Dorsets, with mating in mid-April (spring) and parturition from September to mid-October (autumn). Lamb age ranged from 5-27 days at the beginning of the study. Since this was a pedigree flock, and lamb behaviour may be dependent on their dam, a merit estimated breeding value (EBV) was used to estimate the additive effect of dam genotype on lamb growth to 8 weeks over and above the genes that are inherited by the lamb, for example, the uterine environment or milk traits. To calculate the EBV, an animal model (Wilson et al., 2010) allowing the among-individual variance for a trait to be partitioned into the direct (lamb) and indirect (dam) additive effect and permanent environmental effect was used.

Grazing was managed by strip grazing using an electric fence. Initially the flock had access to an area of 0.69 hectares (ha), which was increased to 1.34 ha after four days, then to a final size of 1.98 ha after a further four days. The field was surrounded on all sides by large hedgerows which provided shade and shelter, and sheep had free access to water in a trough by the hedgerow. Meteorological data were collected daily using a Davis Vantage Pro2 Plus weather station and are summarised in Supplementary Figure 1. The weather during the 2-week deployment was cold and wet for the UK, with a mean daily temperature of 11.1°C and average daily rainfall of 0.63cm. Weather data was summarised into two climatic indices, as used in Ozella et al., (2020):

- Mean daily temperature-humidity index (THI, °C), which combines temperature and humidity (Thom, 1959)
- Mean daily wind-chill index (WCI, °C): combines wind speed with temperature (Tucker et al., 2007):

2.2 Locomotion scoring and treatment of lame sheep

Locomotion scoring was done using a validated 0-6 scale (Kaler et al., 2009). Sheep were scored once each day between 8am-4pm by one observer who walked through the field, this took about an hour each day and provided a locomotion score for each animal each day. Sheep had been acclimatised to being scored throughout September to minimise disruption to their behaviour. Locomotion scores were put into four lameness categories (non-lame: 0-1, mildly lame: 2, moderately/severely lame on one leg: 3-4, and severely lame, involving multiple legs: 5). Sheep that the farmer identified as lame were treated following the farm protocol. There were 9 ewes and 10 lambs treated for interdigital dermatitis by spraying all feet with topical antibiotic, and two lambs were treated with a course of injectable antibiotics for suspected joint ill.

Table 1 Flock characteristics for 50 ewes and their 68 lambs at start of the study period

Characteristic	N (%)	Mean (Range)

Ewes			
Litter size	1	32 (64.0)	-
	2	18 (36.0)	-
Age (years)	-	50 (100.0)	4 (2-9)
Maternal merit (EBV)		50 (100.0)	0.51 (-3.27-3.16)
Lameness score	-	650 (100.0)	0.87 (0-5)
	0	337 (51.8)	-
	1	153 (23.5)	-
	2	98 (15.1)	-
	3	38 (5.8)	-
	4	16 (2.5)	-
	5	8 (1.2)	-
	6	0 (0.0)	
Lambs			
Litter size	1	32 (47.1)	-
	2	36 (52.9)	-
Sex	Female	37 (54.4)	-
	Male	31 (45.6)	-
Age at start (days)	-	68 (100.0)	15 (5-27)
Lameness score	-	885 (99.8)	0.51 (0-5)
Lameness score	0	620 (70.2)	-
	1	159 (18.0)	-
	2	53 (6.0)	-
	3	20 (2.7)	-
	4	21 (2.4)	-
	5	10 (1.1)	-
	6	0 (0.0)	-

1. Number of observations, percentage = percentage of observations

2.3 Bio-logging sensing platform

The study used the Blackdown bio-logging platform (Lewis et al., 2022, Ozella et al., 2020, Ozella et al., 2022, Price et al., 2022) with identical accelerometers and proximity sensors attached to animals.

GENEActiv (Activinsights Ltd., Kimbolton, Cambridgeshire, UK) accelerometers are designed to measure activity in humans by use on a wrist (Eslinger et al., 2011, Rowlands et al., 2014). Use on ewes using a freely rotating neck collar (and on lambs using a chest harness were validated in Price et al., (2022). Devices were set to sample at a rate of 50Hz (+/-8g range at 3.9mg resolution) to maximise data recorded while preserving battery life and could hold 0.5Gb of raw data.

Proximity sensors were designed by the SocioPatterns Collaboration (http://www.sociopatterns.org) and the OpenBeacon project (http://www.openbeacon.org). The sensors exchange low power radio packets, which can be used as a proxy for spatial proximity, described more fully in (Cattuto et al., 2010). The processing of the signals to detect sheep co-located within 1.0-1.5m, is described in Ozella et al., (2022) and Lewis et al., (2022). The proximity sensors had a battery life of ~25 days.

The combined weight of both sensors was ~122 g (proximity sensors ~6g, accelerometers ~16 g, collars/harnesses ~ 100g); less than the recommended threshold of 5% of an animal's body weight (Portugal and White, 2018, Sikes et al., 2016). Ewes and lambs were observed daily to ensure no ill effects and harnesses adjusted if necessary.

2.4 Data Processing

All data were processed to create daily 24-hour summaries (midnight-midnight). Sheep sleep transiently in short bursts (Munro, 1957) and therefore the start of each 24-hour period could be chosen arbitrarily.

2.4.1. Accelerometers

Raw accelerometer data were processed and partitioned into 6 second windows using the dedicated R packages GENEAread (Fang et al., 2020) and GENEAclassify (Campbell et al., 2021). There were 630 ewe-days of activity successfully collected from the 50 ewes. For ewes, the features crucial for activity classification (Price et al., 2022) were extracted for each window: these are the mean and variance of the y axis (to represent neck elevation) and the mean absolute gravity subtracted acceleration. Two random forest classifiers (one to classify posture and one to classify activity) developed in Price et al., (2022) were then applied to label each window with a predicted activity (ruminating, grazing, walking or inactivity) and posture (standing or lying). Posture and activity were predicted with an accuracy of 83.7% and 70.9% respectively.

For lambs, the classifiers created in Price et al., (2022) were adapted and a larger number of features were tested. The top three features were extracted for each window: these were the mean and variance of the y axis and the mean absolute gravity subtracted acceleration to detect posture and the skewness and variance of the y-axis and the mean absolute gravity subtracted acceleration to classify activity. Two random forest classifiers (one to classify posture and one to classify activity) were then applied to label windows with a predicted activity (inactive, sucking or walking (including running)) and posture (standing or lying). Posture and activity were predicted with an accuracy of 93.4% and 87.2% respectively.

There were two postures for both ewes and lambs, these were lying and standing and so posture was represented by the percentage of each day spent standing. There were four behavioural states for ewes – inactive, walking, ruminating and grazing, and three for lambs – inactive, sucking and walking (including running). The total time spent in each behavioural state in each 24 hours was calculated. Compositional data which sums to a constant value, such as the percentage of a day spent in a behavioural state, requires transformation to use in standard statistical approaches (Aitchison, 1986). The time spent in the subset of behavioural states for both ewes and lambs were closed (divided by the total) prior to centred log-ratio (CLR) transformation, where the CLRs are log-transformed parts of the set of compositional variables, centred with respect to their mean across their parts (Greenacre, 2018).

The CLR transformed data were then analysed using principal components analysis with *stats* (R Core Team, 2021) and the first two principal component (PC) scores for activity behaviour compositions for ewes and lambs extracted.

2.4.2 Proximity Sensors

Family groups consisted of a dam and her lamb(s), and out of family groups included all other relationships. Contact data was cleaned and summarised as described in Lewis et al., (2022), into the sum of the duration of contact for sheep with family sheep, and non-family sheep other sheep for each midnight-midnight period, there were 13 days of complete data for 40 ewes and 54 lambs (26 single-raised and 28 twin-raised). Combining the proximity data with the activity data gave 513 complete ewe days of activity and 702 complete lamb days of activity.

2.5 Linear mixed effects models for association between behaviour and lameness

Linear mixed effects models using *lme4* (Bates et al., 2015) in R v4.1.0 (R Core Team, 2021) were used to model factors associated with the outcome variables standing percentage, and PC1 and PC2, for both ewes and lambs. Explanatory variables included as fixed effects were sheep age (years for ewes, days for lambs), litter size (1 or 2 lambs), lameness score category (0/1, 2, 3/4 and 5), contact with family sheep (hours/day), and contact with non-family sheep (hours/day), mean daily THI (°C) (Thom, 1959), mean daily WCI (°C) (Tucker et al., 2007) and total daily rainfall (cm), with random effects included for each sheep and day of study. For lambs, the dam-related variables maternal merit EBV and dam lameness score were also included as fixed effects.
Multi-model inferencing (Burnham and Anderson, 2002) using rank by AIC_c was used to account for model selection uncertainty. Model-averaged coefficients and confidence intervals were calculated for fixed effects using *MuMIn* (Bartoń, 2020) for the 95% confidence set of models (the subset of models whose cumulative Akaike Weight was ≤0.95). Variable importance was calculated as the sum of the Akaike Weights over all models including the variable. Model fit was assessed by leave-one-out-cross validation,

training the model on all but one sheep, and predicting values for that sheep, with mean absolute error calculated over all folds.

3. Results

3.1 Activity time budgets

Ewes stood for about 12 hours per day and spent considerable time grazing (mean 8.7 hours/day) and ruminating (6.5 hours/day). Around 25% of the ewe-day was spent inactive (mean of 6.3 hours/day). The behaviour of single and twin lambs was similar; lambs spent most of their day inactive (mean 15.3 hours/day for single lambs and 14.3 for twin lambs), followed by sucking (mean of 7.0 hours/day for single lambs, and 7.8 for twin lambs), with a small amount of time spent moving (walking/running) (mean of 1.7 hours/day for single lambs, and 1.9 hours/day for twin lambs). Despite inactivity, around half the lamb-day was spent standing (mean = 44.0% for singles, and 50.1% for twin lambs).

Table 2 Percentage of day / time spent in behavioural states for ewes and lambs classified by the random forest algorithm for 513 days of ewe activity and 702 days of lamb activity

	Ewes			**Single lambs**		**Twin lambs**	
Posture	**Mean (% day)**	**SD**	**Posture**	**Mean (% day)**	**SD**	**Mean (% day)**	**SD**
Standing	49.70	8.88	Standing	44.04	10.97	50.13	11.10
Behaviour	**Mean (hours/day)**	**SD**	**Behaviour**	**Mean (hours/day)**	**SD**	**Mean (hours/day)**	**SD**
Inactive	6.31	2.10	Inactive	15.32	2.06	14.33	1.90
Ruminating	6.53	1.44	Sucking	7.01	1.81	7.82	1.67

Grazing	8.71	2.56	-				
Walking	2.45	1.60	Moving	1.68	0.47	1.85	0.51

1. SD = standard deviation

3.2 Compositional analysis of activity summaries

For ewes, PC1 explained 47.1% of the total variance, and PC2 explained 33.2% of the variance (cumulative percentage = 80.3%). PC1 describes 'feeding behaviour': low scores indicate more time spent grazing or ruminating, high scores indicate more time spent walking. PC2 describes 'inactive behaviour': high scores indicate more time spent inactive and low scores indicate more time spent grazing or walking.

For lambs, 65.9% of the variance was explained by PC1, and 34.1% by PC2 (cumulative percentage = 100%). PC1 describes 'inactive behaviour', higher scores indicate more time spent inactive, and lower scores indicate more time spent walking. PC2 describes 'feeding behaviour' by discriminating between type of active behaviour, with high scores for more time sucking and lower scores for more time moving.

Table 3 Principal component loadings for two principal components constructed from the behavioural states for ewes and lambs

Ewes			**Lambs**		
	Loading			**Loading**	
Behaviour	**PC1 Feeding**	**PC2 Inactive**	**Behaviour**	**PC1 Inactive**	**PC2 Feeding**
Inactive	0.146	0.828	Inactive	0.711	
Ruminating	-0.517	0.128	Sucking	-0.524	0.669
Grazing	-0.565	-0.358			
Walking	0.626	-0.411	Moving	-0.469	-0.743

1. PC = principal component

3.3 Mixed effects models of behaviours associated with lameness

For ewes, after adjusting for covariates, standing percentage reduced as lameness score increased (Table 4). Of ewes 'active time', ewes with locomotion scores of 3/4 had higher scores for feeding (PC1) compared with non-lame ewes, indicating lame sheep spent less time grazing or ruminating and more time walking than non-lame ewes (Table 4). Of ewes 'inactive time', ewes became increasingly inactive (PC2) as severity of lameness increased (Table 4). Behaviours were also influenced by age, environment and space available to the sheep (Table 4). The LOOCV of the model fit suggested that sheep behaviour could be predicted from the environmental, social and sheep level factors with reasonable generalisability (Supplementary Figure 2A-C).

Table 4 Model-averaged coefficients from the 95% confidence set of models for standing percentage, 'grazing behaviour' (PC1), and 'inactive behaviour' (PC2) and ewe and environment characteristics for 513 days of ewe-activity

Variable		N (%)	$ß_{full}$	$ß_{conditional}$	LCI	UCI
Standing percentage						
Intercept			73.44	73.44	7.28	139.61
Lameness score	0/1	392 (76.4)	-			
	2	**77 (15.0)**	**-3.05**	**-3.05**	**-4.26**	**-1.83**
	3/4	**36 (7.0)**	**-7.79**	**-7.79**	**-9.70**	**-5.87**
	5	**8 (1.6)**	**-9.47**	**-9.47**	**-12.80**	**-6.13**
Contact non-family sheep	hours/day	513 (100.0)	0.35	0.69	-0.21	1.60
Contact family sheep	**hours/day**	**513 (100.0)**	**-0.64**	**-0.65**	**-1.10**	**-0.20**
Ewe age	years	513 (100.0)	-0.37	-0.75	-1.75	0.26
Litter size	1	331 (64.5)	-			
	2	182 (35.5)	1.42	2.74	-0.80	6.28
Mean daily WCI	**°C**	**513 (100.0)**	**2.01**	**2.38**	**0.17**	**4.59**

Variable		N (%)	ß full	ß conditional	LCI	UCI
Mean daily THI	°C	513 (100.0)	-0.83	-1.25	-2.65	0.15
Total daily rainfall	**cm**	**513 (100.0)**	**2.94**	**3.37**	**0.64**	**6.11**
Field size	0.69 ha	160 (31.2)	-			
	1.34 ha	58 (30.8)	1.85	2.29	-0.85	5.43
	1.98 ha	**195 (38.0)**	**4.45**	**5.51**	**1.56**	**9.46**
PC1: 'Feeding behaviour'						
Intercept			0.42	0.42	-3.30	4.13
Lameness score	0/1	392 (76.4)	-			
	2	77 (15.0)	0.04	0.04	-0.16	0.25
	3/4	**36 (7.0)**	**1.05**	**1.05**	**0.73**	**1.38**
	5	8 (1.6)	0.45	0.45	-0.11	1.01
Contact non-family sheep	hours/day	513 (100.0)	0.06	0.11	-0.04	0.26
Contact family sheep	**hours/day**	**513 (100.0)**	**0.08**	**0.09**	**0.01**	**0.17**
Ewe age	years	513 (100.0)	-0.06	-0.14	-0.36	0.07
Litter size	1	331 (64.5)	-			
	2	182 (35.5)	-0.02	-0.08	-0.85	0.69
Mean daily WCI	°C	513 (100.0)	-0.03	-0.09	-0.27	0.09
Mean daily THI	°C	513 (100.0)	0.00	-0.01	-0.15	0.13
Total daily rainfall	cm	513 (100.0)	-0.08	-0.19	-0.53	0.14
Field size	0.69 ha	160 (31.2)	-			

Variable		N (%)	$ß_{full}$	$ß_{conditional}$	LCI	UCI
	1.34 ha	**58 (30.8)**	**0.45**	**0.54**	**0.12**	**0.96**
	1.98 ha	195 (38.0)	-0.06	-0.07	-0.53	0.39
PC2: 'Inactive behaviour'						
(Intercept)			-3.48	-3.48	-8.19	1.24
Lameness score	0/1	392 (76.4)	-			
	2	**77 (15.0)**	**0.24**	**0.24**	**0.10**	**0.38**
	3/4	**36 (7.0)**	**0.44**	**0.44**	**0.22**	**0.66**
	5	**8 (1.6)**	**0.53**	**0.53**	**0.14**	**0.92**
Contact non-family sheep	hours/day	513 (100.0)	-0.03	-0.07	-0.17	0.03
Contact family sheep	**hours/day**	**513 (100.0)**	**0.08**	**0.08**	**0.03**	**0.13**
Ewe age	**years**	**513 (100.0)**	**0.11**	**0.13**	**0.02**	**0.24**
Litter size	1	331 (64.5)	-			
	2	182 (35.5)	-0.10	-0.23	-0.61	0.14
Mean daily WCI	**°C**	**513 (100.0)**	**-0.19**	**-0.21**	**-0.36**	**-0.06**
Mean daily THI	**°C**	**513 (100.0)**	**0.09**	**0.11**	**0.02**	**0.20**
Total daily rainfall	**cm**	**513 (100.0)**	**-0.32**	**-0.32**	**-0.49**	**-0.15**
Field size	0.69 ha	160 (31.2)	-			
	1.34 ha	**58 (30.8)**	**-0.26**	**-0.29**	**-0.50**	**-0.08**
	1.98 ha	**195 (38.0)**	**-0.33**	**-0.37**	**-0.62**	**-0.11**

1. N = number of observations, PC = principal component, ß= model-averaged coefficient, LCI = lower confidence interval, UCI = upper confidence interval

2. β_{Full} is the average coefficient where it is assumed that the variable is included in every model, but in some models the corresponding coefficient (and its respective variance) is set to zero. $\beta_{Conditional}$ is the average over the models where the parameter is included.

3. 95% confidence set of models where the $\sum$ $Akaike\ Weight \leq 0.95$ (Standing percentage: 89/512 models, PC1: 158/512 models, PC2: 47/512 models).

4. Variable importance ($\sum$ $Akaike\ Weight$) over the whole model set is shown in Supplementary Figure 2.

For lambs, higher lameness scores were associated with reduced standing percentage (Table 5) and as with ewes, time spent 'inactive' increased as lameness score increased, indicating lame lambs spent more time inactive as lameness became more severe than non-lame lambs. Lambs with ewes that with lameness scores of 3/4 were associated with more 'inactive' time (Table 5). 'Inactive' behaviour was also associated social contact, age and environment (Table 5).

Lame lambs spent more time feeding and less time walking than non-lame lambs and lambs with dams with lameness scores of 3/4 also spent more time feeding (Table 5). There was no association between climate and feeding but lamb feeding behaviour did increase as field size increased (Table 5), although, this could be confounded by lamb age since field size was positively correlated with lamb age.

Table 5 Model-averaged coefficients from the 95% confidence set of models for standing percentage, 'inactivity' (PC1), and 'feeding' behaviour (PC2) and lamb and their dam characteristics and environmental characteristics from the 95% confidence set of models for 54 lambs over the 13-day study period

Variable		N (%)	ß$_{full}$	ß$_{conditional}$	LCI	UCI
Standing percentage						
Intercept			143.68	143.68	82.34	205.02
Lamb lameness score	0/1	616 (87.7)	-			
	2	**46 (6.6)**	**-3.13**	**-3.13**	**-5.02**	**-1.24**

Variable		N (%)	ß full	ß conditional	LCI	UCI
	3/4	**31 (4.4)**	**-6.88**	**-6.88**	**-9.57**	**-4.18**
	5	**9 (1.3)**	**-12.90**	**-12.90**	**-16.96**	**-8.83**
Contact family sheep	**hours/day**	**702 (100.0)**	**0.30**	**0.41**	**0.01**	**0.81**
Contact non-family sheep	**hours/day**	**702 (100.0)**	**0.24**	**0.34**	**0.01**	**0.67**
Lamb age	days	702 (100.0)	0.14	0.29	-0.11	0.69
Lamb sex	Female	351 (50.0)	-			
	Male	351 (50.0)	-0.74	-2.14	-6.75	2.48
Litter size	1	338 (48.1)	-			
	2	364 (51.9)	3.35	4.77	-0.01	9.56
Dam lameness score	0/1	526 (74.9)	-			
	2	103 (14.7)	0.29	0.71	-0.69	2.10
	3/4	60 (8.5)	-0.64	-1.55	-3.67	0.58
	5	13 (1.9)	1.13	2.75	-0.80	6.31
Maternal Merit EBV	-	702 (100.0)	0.07	0.25	-2.59	3.09
Mean daily THI	**°C**	**702 (100.0)**	**-2.65**	**-2.69**	**-4.00**	**-1.37**
Mean daily WCI	**°C**	**702 (100.0)**	**3.66**	**3.73**	**1.82**	**5.65**
Total daily rainfall	**cm**	**702 (100.0)**	**3.08**	**3.40**	**1.16**	**5.63**
Field size	0.69 ha	216 (30.1)	-			
Field size	1.34 ha	216 (30.1)	0.21	0.57	-2.50	3.65

Variable		N (%)	ß$_{full}$	ß$_{conditional}$	LCI	UCI
Field size	1.98 ha	270 (38.5)	1.23	3.35	-0.49	7.18
PC1: 'Inactive behaviour'						
Intercept			-14.31	-14.31	-23.87	-4.74
Lamb lameness score	0/1	616 (87.7)	-			
	2	**46 (6.6)**	**0.58**	**0.58**	**0.36**	**0.80**
	3/4	**31 (4.4)**	**1.10**	**1.10**	**0.79**	**1.41**
	5	**9 (1.3)**	**2.08**	**2.08**	**1.61**	**2.56**
Contact family sheep	**hours/day**	**702 (100.0)**	**-0.06**	**-0.07**	**-0.11**	**-0.02**
Contact non-family sheep	**hours/day**	**702 (100.0)**	**-0.07**	**-0.07**	**-0.11**	**-0.03**
Lamb age	**days**	**702 (100.0)**	**-0.05**	**-0.05**	**-0.09**	**-0.01**
Lamb sex	Female	351 (50.0)				
	Male	351 (50.0)	-0.00	0.01	-0.41	0.44
Litter size	1	338 (48.1)	-			
	2	364 (51.9)	-0.23	-0.39	-0.84	0.06
Dam lameness score	0/1	526 (74.9)	-			
	2	103 (14.7)	-0.01	-0.01	-0.18	0.15
	3/4	**60 (8.5)**	**0.49**	**0.49**	**0.24**	**0.74**
	5	13 (1.9)	-0.14	-0.15	-0.56	0.27
Maternal Merit EBV	-	702 (100.0)	-0.02	-0.07	-0.33	0.18
Mean daily THI	**°C**	**702 (100.0)**	**0.39**	**0.40**	**0.20**	**0.60**

Variable		N (%)	ß$_{full}$	ß$_{conditional}$	LCI	UCI
Mean daily WCI	**°C**	**702 (100.0)**	**-0.55**	**-0.56**	**-0.85**	**-0.27**
Total daily rainfall	**cm**	**702 (100.0)**	**-0.42**	**-0.48**	**-0.81**	**-0.14**
Field size	0.69 ha	216 (30.1)	-			
Field size	1.34 ha	216 (30.1)	-0.03	-0.08	-0.54	0.38
Field size	1.98 ha	270 (38.5)	-0.20	-0.51	-1.07	0.05
PC2: 'Feeding behaviour'						
Intercept			0.03	0.03	-2.60	2.67
Lamb lameness score	0/1	616 (87.7)	-			
	2	**46 (6.6)**	**0.14**	**0.24**	**0.04**	**0.44**
	3/4	31 (4.4)	0.12	0.20	-0.08	0.48
	5	9 (1.3)	0.08	0.14	-0.29	0.56
Contact family sheep	hours/day	702 (100.0)	-0.02	-0.03	-0.07	0.01
Contact non-family sheep	**hours/day**	**702 (100.0)**	**-0.09**	**-0.09**	**-0.12**	**-0.05**
Lamb age	days	702 (100.0)	0.02	0.03	0.00	0.07
Lamb sex	Female	351 (50.0)	-			
	Male	351 (50.0)	-0.17	-0.31	-0.70	0.08
Litter size	1	338 (48.1)	-			
	2	364 (51.9)	0.02	0.09	-0.34	0.51
Dam lameness score	0/1	526 (74.9)	-			
	2	103 (14.7)	0.02	0.03	-0.12	0.17

Variable		N (%)	ß$_{full}$	ß$_{conditional}$	LCI	UCI
	3/4	**60 (8.5)**	**0.21**	**0.28**	**0.06**	**0.50**
	5	13 (1.9)	0.19	0.26	-0.11	0.63
Maternal Merit EBV	-	702 (100.0)	-0.06	-0.14	-0.38	0.09
Mean daily THI	°C	702 (100.0)	0.00	-0.01	-0.11	0.09
Mean daily WCI	°C	702 (100.0)	-0.02	-0.05	-0.19	0.08
Total daily rainfall	cm	702 (100.0)	0.13	0.22	-0.03	0.46
Field size	0.69 ha	216 (30.1)	-			
Field size	**1.34 ha**	**216 (30.1)**	**0.30**	**0.34**	**0.02**	**0.67**
Field size	**1.98 ha**	**270 (38.5)**	**0.46**	**0.53**	**0.16**	**0.90**

1. N = number of observations, PC = principal component, ß = model-averaged coefficient, LCI = lower confidence interval, UCI = upper confidence interval
2. β_{Full} is the average coefficient where it is assumed that the variable is included in every model, but in some models the corresponding coefficient (and its respective variance) is set to zero. $\beta_{Conditional}$ is the average over the models where the parameter is included.
3. 95% confidence set of models is the model set is where the $\sum Akaike\ Weight \leq 0.95$ (standing percentage: 90/4096 models), PC1:1231/4096 models, PC2: 451/4096 models).
4. Variable importance ($\sum Akaike\ Weight$) over the whole model set is shown in Supplementary Figure 3.

4. Discussion

This is the first study to determine behavioural changes associated with lameness within a commercial flock of sheep. The results demonstrate lameness is associated with reduced activity in both ewes and lambs. Specifically, lame ewes stand less and are more inactive, that is they spend a lower portion of their active time grazing and ruminating compared to non-lame ewes. Lame lambs also stand less, and are more inactive, spending a lower proportion of their time moving. Lamb inactivity also increases when their dam is moderately/severely lame. All these behavioural changes detected by biologgers could potentially be used in commercial applications to give farmers ‘early warning’ of lameness. This would lead to improved welfare for individual sheep treated more rapidly and reduced incidence of lameness in flocks.

Our study has identified behavioural changes in sheep with generic lameness using continuous data from biologgers. Other studies using biologging technology have also reported differences between lame and non-lame animals using continuous biologging data, for example, lambs with footrot have shorter lying bouts (Härdi-Landerer et al., 2017), lame cows walk slower (Thorup et al., 2015), lame cows reduce grazing time and increase inactive time (Riaboff et al., 2021) and lame sows walk slower and spend less time standing (Grégoire et al., 2013) compared with non-lame animals. The current study also contributes information on lameness in sheep to other studies of other health conditions of ewes and lambs that can be detected using continuous activity data in ewes (Burgunder et al., 2018, Falzon et al., 2013, Gurule et al., 2022, Trieu et al., 2022) and lambs (Cronin et al., 2016, Ikurior et al., 2020, Högberg et al., 2021).

Within the mixed effects models, locomotion score was used as a categorical variable, with the reference category of score 0/1 as sound sheep. On the scoring system used (Kaler et al., 2009), sheep are typically considered lame at score 2 or more, where a clear shortening of stride is present. The results indicate that behavioural differences only occur when sheep are non-weight bearing on a limb, when standing and moving (score 3 and 4) (Table 4). It was hypothesised that sheep would behave most differently at score 5, when lame on multiple legs, but there were few observations of sheep lame at this score, which reduced the power to detect differences.

The relatively short period of the current study precludes us from determining the directionality of lameness and some behavioural effects: does lameness cause all of these behaviour changes or are sheep that behave in certain ways more likely to become lame? Some effects, such as reduced standing percentage when sheep are lame, seem intuitively to be a pain response, since lameness causes pain (Ley et al., 1994). However, high ‘feeding behaviour’ scores in lambs which were associated with mild lameness score 2, are possibly causal since lambs which spend more time in close contact with their dams are more likely to become lame (Lewis et al., 2022).

Lambs with moderately/severely lame dams were more inactive (Table 5) than lambs with non-lame dams highlighting that dam behaviour impacts lamb behaviour. Further studies of longer duration would enable us to understand causality and whether inactive lambs become more active once their dam becomes sound. Longer studies will become possible as biologging technology improves through improved real-time data communications and longer battery life.

It was important to investigate and control for environmental influences since these affect sheep behaviour and aspects of environmental conditions would need to be included in commercial applications to automatically detect lame sheep. Environmental drivers of behaviour are likely to include season, production period, climate, and resources, such as shelter. The analyses used enabled us to disentangle the associations between lameness and behaviour from the environment. In other studies, wind-chill index (Ozella et al., 2020), temperature (Doyle et al., 2016) and rainfall (Doyle et al., 2016), all led to increased time ewes spent clustered. In the current study, both ewes and lambs had lower 'inactivity' scores and higher standing percentages in colder and wetter weather. This could be because ewes avoid grazing while it is raining (Champion et al., 1994), but also they may be more inclined to graze after heavy rainfall when the grass has been refreshed. Similarly, ewes may prefer to avoid lying on wet ground, housed sheep have lying preferences for types of flooring (Færevik et al., 2005) and it is possible outdoor sheep also choose when to lie based on ground conditions. Standing in wet weather may also aid thermoregulation, reduction in lying time is a key strategy for thermoregulation in sheep (Bøe, 1990).

Sheep are social animals and develop social bonds with other individuals, based on relationship, age and personality (Michelena et al., 2009, Ozella et al., 2020). Family bonds are some of the strongest social bonds within sheep flocks (Ozella et al., 2022) and most ewe-lamb contact occurs when the ewe is inactive and they lie together (Morgan and Arnold, 1974). Combining accelerometer and proximity data revealed that ewes with high lying percentage and 'inactive' behaviour had more contact with their lambs (consistent with Morgan and Arnold, 1974), and vice versa for lambs. This difference may be because lambs come to their dam who remains stationary for contact whilst twin lambs can keep in contact whilst standing and active: in the same study twin had strong bonds with each other and spent less time with their mother than single lambs (Ozella et al., 2022).

Lambs ranged from 5-41 days old from the youngest at the start of the study to the oldest at the end of the study. As lambs got older 'inactivity' decreased, which is consistent with observational studies. In the first four weeks of life lamb activity increases with age and lambs become increasingly independent from their dam (Ewbank, 1964, Ewbank, 1967, Morgan and Arnold, 1974). In the study, 'feeding behaviour' was not associated with age, and it may be that differences in sucking behaviour only occur as lambs approach weaning age, naturally this is around 6-8 months. 'Feeding behaviour' was made up of time spent sucking, and time spent running/walking, some of the latter would include time spent playing, which is a normal behaviour in young lambs (Morgan and Arnold, 1974). Lambs which are lame may be trading 'essential' behaviour, i.e. sucking, in favour of 'luxury' behaviours, such as playing, demonstrating lamb welfare is adversely impacted by lameness. An estimation of the ewe's maternal merit (ability to feed and raise lambs) was included as a possible predictor of lamb behaviours but was not associated with behaviour (Table 5).

There is increasing evidence that there is wide variability in individual farm animal behaviour (Occhiuto et al., 2022, Thorup et al., 2020), and the current study supports this (Table 2). Individual animal movement varies from day-to-day, as seen in horses (Sepulveda Caviedes et al., 2018), and quantification of the deviation from an individual animal's normal range to abnormal for that individual is essential to automate identification of diseased individuals accurately. This 'deviation from expected normal' approach has been used to identify clinical mastitis in dairy cows (Kok et al., 2021).

Our study provides new evidence that there are behavioural differences in sheep with different lameness scores, and that these have potential for future tools to automatically detect lameness in sheep. Flock incidence and prevalence of lameness is lower when sheep are treated within 3 days of becoming lame (Kaler et al., 2010, Wassink et al., 2010a). If increased 'inactivity' can be automatically detected in sheep with locomotion score 2, the typical threshold for defining lameness, then biologging data may be a useful tool to indicate when a sheep should be examined, allowing farmers to save time identifying lame sheep by visual assessment.

5. Conclusion

It is possible to identify lame ewes and lambs through analysis of continuously recording biologging data. Lame sheep are more inactive and less likely to feed. Models that include adjustments for social behaviour, climate and other environmental covariates enable the elucidation of the change in behaviour attributable to lameness.

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8. Data statement

Data is available on request.

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10. Declaration of interests

Joss Langford is a director of Activinsights Ltd. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

11. Contributions

KL analysed the data and wrote the manuscript draft. EP and JL processed the accelerometer data, LO and CC processed the proximity sensor data, and EP, JL and KL collected the farm data. LG, DC and JL conceived the study design and aall authors contributed to, reviewed and approved the submitted version of the manuscript.

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