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Animal Welfare 2020, 29: 339-352
ISSN 0962-7286
doi: 10.7120/09627286.29.3.339

Duration of confinement and pen-type affect health-related measures of welfare in lactating sows

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Abstract

*Temporary crating is considered as a step towards improved welfare in lactating sows. Therefore, the aim of this study was to investigate effects of confinement period (CP) and farrowing pen-type (PT) on health-related measures. Four hundred and thirteen sows were kept in five PT with four CP each: CP 0-sows were not confined; CP 3-sows were crated postpartum for three days; CP 4- and CP 6-sows were crated from a day prior to expected farrowing until day 4 and 6 postpartum, respectively. Alterations in different body regions were recorded when sows were moved to the pens and in weeks 1, 3 and 4 postpartum. CP 6-sows displayed significantly more lesions on their back than CP 0- and CP 3-sows. Odds ratios of teat lesions were markedly higher in CP 4-sows than in all other CP. Pen-type P (Pro Dromi) resulted in more neck/back/body side injuries, claw horn changes and lame sows compared to all other PT. High odds ratios were also found for neck injuries in PT K (Knick), shoulder sores in PT K and T (Trapez), injured teats in PT F (Flügel) and body side injuries in PT S (SWAP). The types of lesions found in the present study are similar to those reported for crates caused by pen structures. While an overall assessment of pig (*Sus scrofa domesticus*) production husbandry systems must also take piglet welfare into account, this study showed that keeping confinement periods as short as possible improves sow welfare and systems should be adapted to also cater for the needs of sows.*

Keywords: *animal welfare, farrowing systems, pathological alterations, skin lesions,* Sus scrofa domesticus*, temporary crating*

Introduction

Since the 1970s, pre-partum and lactating sows across the world have been kept in farrowing crates to reduce required space, provide a safe working environment, reduce workload and reduce piglet mortality (for a review, see Edwards & Fraser 1997). Piglet mortality is particularly high during the first few days of life (Dyck & Swierstra 1987; Marchant *et al* 2001). The main reason for piglet death is crushing by the sow (from birth until weaning: 29.1% of liveborn mortality in Kielland *et al* 2018, 55.0% in Kilbride *et al* 2012 and 74.6% in Marchant *et al* 2001). Some studies have shown the risk of crushing to be higher in free farrowing pens compared to crates (Marchant *et al* 2000; Weber *et al* 2007; Kilbride *et al* 2012; Hales *et al* 2014). In pen systems, early piglet losses are lower when the sow is confined for the first days after farrowing (Moustsen *et al* 2013; Hales *et al* 2015; Olsson *et al* 2018; Nicolaisen *et al* 2019).

The effects of crating on sow welfare have been investigated previously (Cronin *et al* 1994; Lawrence *et al* 1994; Jarvis *et al* 2001), and more recently public concern has increased. To date, Norway, Sweden and Switzerland have banned farrowing crates completely, whereas in Denmark 10% of all lactating sows must be loose-housed by 2021. In Austria, the public's demand for improved sow welfare has led to an amendment of the Austrian animal welfare legislation (1 Tierhaltungsverordnung [BMGF 2004], amendment BGBl II Nr 61/2012 [BMG 2012]). The amendment states, *inter alia*, that from 2033 crating of sows will only be allowed until the end of the 'critical phase of life' of piglets. By 2033, all farrowing pens on Austrian farms must then measure at least 5.5 m^2 with a minimum length of 1.6 m and the crate must be adjustable in width and length to the individual sow.

So far, research into the effects of temporary confinement on sows and piglets has focused mainly on piglet mortality (Moustsen *et al* 2013; Hales *et al* 2015). Therefore, little is known about the effects of temporary crating on sow welfare. In general, designing a farrowing and lactation environment that fulfils multiple, sometimes divergent and

Table 1 Characteristics of pen-types.

Pen-type	Pen dimensions	Crate design	Crate dimensions	Described in Appendix
F (Flugel)	5.50 m² (2.10 × 2.62 m)	Telescopic design; width and length of both side elements adjustable; rear door as wings	(1.57–2.02) × (0.49–0.67) m	Figure 1
K (Knick)	5.50 m² (2.10 × 2.62 m)	Telescopic design; length of both side elements adjustable; width adjustable on one side	(1.25–1.85) × (0.71–0.81) m	Figure 2
S (SWAP)	6.00 m² (2.00 × 3.00 m)	Crate formed by side wall and hinged swing fixed to the front wall of the pen; width modified by adaptation of a flexible element in the back	1.86 × (0.55–0.99) m	Figure 3
T (Trapez)	5.50 m² (2.20 × 2.50 m)	Flexible wings in the rear for length adjustment; crate equipped with a wheel for width adjustment	(1.70–1.90) × (0.63–0.72) m	Figure 4
P (Pro Dromi)	7.29 m² (3.36 × 2.17 m)	Side elements serve as pen walls when the crate is open; fixed to trough construction when crate is closed	1.92 × 0.62 m	Figure 5

Crate dimensions excluding trough, with minimum and maximum values for length × width where applicable; width measured at rear end.

changing needs of sows and piglets as well as of farmers is an ongoing challenge (for a review, see Baxter *et al* 2011). Farrowing crates have been reported to cause serious skin lesions (Boyle *et al* 2002), which can be observed in crated gilts as soon as 24 h after placement (Boyle *et al* 2000). Space allowance and floor type are considered two of the most crucial risk factors for injuries (Baxter *et al* 2011). More specifically, important floor characteristics are slip-resistance, abrasiveness, surface profile, hardness, slat width and thermal resistance (Baxter *et al* 2011). Confined sows often hit the crate when lying down or standing up (Troxler & Weber 1988; Harris & Gonyou 1998), which has been linked to increased injury rates (Bonde *et al* 2004). Moreover, sows in farrowing crates show greater prevalence of skin lesions on the udder and injured teats as well as limb alterations compared to sows kept in free farrowing pens (Verhovsek *et al* 2007).

As part of a larger project (Pro-SAU) investigating the effects of different durations of confinement and pen design on piglet mortality, sow and piglet welfare, economic efficiency and occupational safety, this study focuses on health-related measures of welfare in lactating sows. We examined selected parameters of physical appearance in sows to draw conclusions on the effects of temporary crating of variable duration in five different farrowing pen-types on sow health and welfare. The hypothesis was that within the observed set-ups of temporary confinement, confinement period and pen-type have significant effects on the selected health-related measures of sow welfare.

Materials and methods

Ethical statement

Pro-SAU was authorised by the Committee of Animal Experimentation of the Austrian Federal Ministry of Science, Research and Economy (GZ: BMWFV-68.205/0082-WF/II/3b/2014) according to the Austrian Tierversuchsgesetz 2012, BGBl I Nr 114/2012 (BMWF 2012) and by the Ethical Committee of the University of Veterinary Medicine Vienna.

Study animals and management

This study was conducted between April 2014 and August 2016 on three teaching and research farms (A, B, C) in Austria. Farm A's herd consisted of 600 sows including 'PIC' - crossbreeds and F1 crosses (Landrace × Large White), farm B's herd consisted of 55 Large White sows and farm C's herd consisted of 120 Large White and Landrace × Large White sows. Parity of animals included in the study ranged between 1 and 8. Piglets were weaned at three weeks of age on farm A and at four weeks on farms B and C. All herds were managed as an all in, all out system, but other routine management procedures were farm-specific. Procedures, such as induction of farrowing (only after 116 days of pregnancy) and cross-fostering (12 to 36 h postpartum), were carried out according to best practice procedures as defined in a project handbook (Heidinger *et al* 2017). Sows on all farms were under farm-specific restricted feeding regimes. All of them were provided with predefined amounts of enrichment and nest-building material that could be chewed, investigated and moved around as required by the Austrian Tierhaltungsverordnung (BMG 2012).

Experimental design

Each farm was equipped with at least three out of five different experimental PT, all allowing temporary confinement of sows: Flügel (F), Knick (K), SWAP (S), Trapez (T), Pro Dromi (P). Pen-types F, K, S and T were available on farm A with four pens each; PT F, K and T were available on farm B with two pens each; and pen-types F, S, T and P were available on farm C with four pens each. Dimensions of PT were the same across all farms. For detailed descriptions of all PT see Table 1 and Figures 1–5 in the Appendix (supplementary material to papers published in *Animal Welfare*: https://www.ufaw.org.uk/the-ufaw-

Table 2 Number of batches and sows for each farm and combination of confinement period (CP) and pen-type (PT).

Farm	Batches (n)	Sows (n)	PT	Breed	CP							
					0		3		4		6	
					Sows	Gilts	Sows	Gilts	Sows	Gilts	Sows	Gilts
A	27	190	F	PIC	14	6	20	5	19	6	24	8
			K	PIC	20	7	18	6	17	6	18	8
			S	PIC	14	3	14	3	18	6	10	6
			T	PIC	15	6	19	3	14	6	23	6
B	19	72	F	LW	9	2	6	2	5	3	6	0
			K	LW	9	2	7	1	7	1	8	0
			T	LW	8	2	8	0	5	2	8	0
C	23	151	F	LW	12	0	10	1	11	1	12	1
				LR × LW	3	1	2	3	2	2	1	3
			P	LW	11	0	9	1	11	1	5	3
				LR × LW	3	2	4	2	1	4	3	4
			S	LW	12	2	10	4	13	0	12	1
				LR × LW	1	3	1	3	1	1	2	1
			T	LW	10	2	12	0	3	4	12	0
				LR × LW	3	1	3	1	5	4	1	2

CP 0-sows were not confined;
CP 3-sows were crated postpartum for 3 days;
Sows in CP 4 and CP 6 were crated from a day prior to expected farrowing until day 4 and 6 postpartum, respectively;
Pen-types (PT): F: Flügel, K: Knick, P: Pro Dromi, S: SWAP, T: Trapez;
Breeds: PIC (Hybrid), LW (Large White) and crossbreds of Landrace and Large White (LR × LW).

journal/supplementary-material on the UFAW website). Data were collected during 27 and 19 batches on farms A and B, respectively. Sows stayed in the farrowing pen from approximately five days before the expected parturition date (on group-level) until weaning. On farm C, in ten out of 23 batches, sows and piglets were moved to standard farrowing pens approximately ten days after farrowing (short batches), thus reducing the length of the study period. This approach was implemented to increase the sample size specifically around the first days of lactation which are particularly relevant for piglet survival. In all farms, all gilts of a group were assigned equally to all pen-types and after that pens were filled up with sows randomly assigned to treatments. Most of the sows participated in the experiment more than once (see Data collection in the Appendix: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material). Severely sick animals (eg sows with lameness score > 1) were excluded from the trial before entering the experimental pens. For further details on the experimental set-up, see Table 2.

An assessment protocol was developed based on previous projects (Leeb *et al* 2010) and other animal-based welfare assessment protocols (Welfare Quality® 2009). The following parameters were included: shoulder sores, skin injuries (separately scored for the body regions: neck, back, head, ears, shoulder, side, hindquarters, legs, front udder region, rear udder region and vulva), teat injuries (number of injured front/rear teats, number of partial/missing front/rear teats), swellings of hind limbs, alterations of (dew) claws and lameness. Examinations were carried out when the sows were moved to the farrowing unit (day [D]1) and 4–7 days (D2), 17–20 days (D3) as well as 25–28 days (D4) after farrowing. A detailed description of data assessment is provided in Data collection in the Appendix (https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material). In total, 2,177 assessments of 413 animals were considered for statistical analysis (see Table 2).

Confinement periods

Four different confinement periods (CP) were applied: in CP 0 sows were not confined at all. In CP 3 sows were crated from the end of farrowing to day 4 after farrowing, resulting in a median duration of 2.92 days (min = 1.98, max = 3.65; n = 85 sows for which exact time of closing and opening the crate are available) of confinement. In CP 4, sows were confined from a day before the expected farrowing date until day 4 after farrowing (median duration = 5.02 days, min = 2.85, max = 9.01; n = 88 sows), and in CP 6 from the day before expected farrowing date to

Table 3 Total number of observations within scores of parameter, total and relative number of observations unequal to 0 and 'combined parameter' (where applied).

Parameter	Score			n > 0	% > 0	Combined parameter
	0	1	2			
Injuries head	2,031	123	15	138	6.4	Injuries head region
Injuries ears	2,092	71	7	78	3.6	
Injuries neck	2,060	100	17	117	5.4	
Injuries back	1,881	227	65	292	13.4	
Shoulder sore	1,994	124	45	169	7.8	
Injuries shoulder	1,931	183	55	238	11.0	Injuries body side
Injuries side	1,920	175	68	243	11.2	
Injuries hindquarters	1,904	191	62	253	11.7	
Injuries front udder region	2,072	60	22	82	3.8	Injuries udder region
Injuries rear udder region	1,420	421	294	715	33.5	
Number of injured front teats	1,977	[1]	[1]	179	[1]	Number of injured teats
Number of injured rear teats	1,458	[1]	[1]	694	[1]	
Number of partial/missing front teats	2,137	[1]	[1]	17	[1]	Number of partial/missing teats*
Number of partial/missing rear teats	2,057	[1]	[1]	93	[1]	
Swelling in region of front udder*	2,147	8	[2]	8	0.4	Swelling(s) in region of udder*
Swelling in region of rear udder*	2,121	31	[2]	31	1.4	
Injuries vulva	2,045	101	[2]	101	4.7	
Vulval scarring/missing parts*	2,104	51	[2]	51	2.4	
Injuries legs	2,024	118	9	127	5.9	
Swellings hind legs	2,097	61	[2]	61	2.8	
Claw length*	2,116	40	[2]	40	1.9	
Infection of claws/'panaritium'*	2,071	61	[2]	61	2.9	
Changes claw horn	1,795	275	[2]	275	13.3	
Alterations dew claws*	1,487	634	[2]	634	29.9	
Lameness	1,967	166	6	172	8.0	

[1] Count measure;
[2] Only score 1 possible;
* Not considered for statistical modelling.

day 6 after farrowing (median duration = 6.15 days, min = 4.93, max = 10.00; n = 74 sows).

Design of farrowing pens

Five different farrowing pen-types (PT) were investigated. Three pen-types had been developed by partners from Austrian scientific and advisory institutions, housing-construction companies and farmers (pen-types F, K, T) and two were already commercially available on the European market (S, P). All PT fulfilled the minimum Austrian legal requirements at the time of the study. Features of pen-types are described in Table 1. Due to slipperiness of the floor, some modifications as described in Figure 5 in the Appendix (https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) were made during the experiment.

Data processing and statistical analysis

Prevalences of injuries in certain body regions, but especially lesions of high severity (score 2) were too low to allow modelling as ordinal or nominally scaled responses. We therefore aggregated lesions of different body parts (Table 3), and scores 0, 1 and 2 were dichotomised into 0/1 by merging scores 1 and 2 to score 1. Prevalences of the parameters 'swelling of front/rear udder region', 'vulvar scarring/missing parts', 'claw length', 'infection of claws/panaritium' were generally too low to allow for hypothesis testing (see Table 3 and Data collection and Table 1 in the Appendix: https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material).

Data processing and statistical analyses were carried out using SPSS 22.0 and 24.0 (IBM Corp 2013, 2016, Armonk, New York, USA) and R version 3.3.2 (R Core Team 2013). The following R packages provided additional functionality for statistical analysis: 'car' (Fox & Weisberg 2011), 'MASS' (Venables & Ripley 2002), 'ggplot2' (Wickham 2009), 'lme4' (Bates *et al* 2015), 'aod' (Lesnoff & Lancelot 2012), 'lattice' (Sarkar 2008), 'vcd' (Meyer *et al* 2006, 2017), 'vcdExtra' (Friendly 2017), 'MuMIn' (Barton 2017), 'piecewiseSEM' (Lefcheck 2016), 'DHARMa' (Hartig 2016). To avoid carry-over effects from the gestation pen, all parameters of sows with score 1 on D1 (including also D2–D4) were omitted from further analyses. Dichotomised binary response variables were analysed with generalised linear mixed models using function glmer from package lme4 with a logit-link function. We employed a significance cut off of 5% after multiple testing correction according to Holm (1979) when applicable. Type of farrowing pen, confinement period and the interaction between these two main effects were always included as categorical fixed effects in the full model. Farm, breed and individual sow number were fitted as random intercept effects. Additionally, to model progression of lesions during the observation period, we added a random slope effect with repeated measures on D1–D4 for each sow within parity ('litter ID'), whereas assessment days (D1–D4) were fitted as continuous effect. Depending on Bayesian Information Criteria of competing models, age of sow was defined either as a categorical ('sow/gilt') or as a continuous ('parity') effect recorded as age in litter numbers. Additional factors (BCS, lameness, mastitis metritis agalactia, litter size) were included whenever considered as potentially influencing. The parameter 'number of injured teats' was negatively binomially distributed and modelled with function 'glmer.nb'. Applying the principle of parsimony, we performed backward model selection based on the Bayesian Information Criterion (BIC) to create final models that included significant fixed effects only.

The following equation indicates the mathematical formula for statistical modelling:

$$Y = PT + CP + PT \times CP + D + age + breed + farm + sow\ number + litter\ ID + other + e$$

Where, PT signifies fixed categorical effect of pen-type with 5 levels, CP is the fixed categorical effect of confinement period with 4 levels, PT × CP the interaction of PT and CP, D the fixed continuous effect, age the fixed continuous effect recorded in litter number or as categorical effect with levels gilt and sow, breed the random effect with 3 levels, farm the random effect with 3 levels, sow number the random effect with 413 levels, litter ID the random slope effect for each sow within parity with repeated measures on D1–D4, other the fixed categorical effect BCS (2 levels), lameness (2 levels), mastitis metritis agalactia (2 levels) or fixed continuous effect litter size and e the residual effect.

Results

Total and relative numbers of scores for all assessed parameters are presented in Table 3, and Table 1 in the Appendix (https://www.ufaw.org.uk/the-ufaw-journal/supplementary-material) indicates prevalences and frequencies for D3. Overall prevalences exceeding 10% were found for injuries of the back, shoulder, side and hindquarters, changes of claw horn and alterations of dew claws. Injuries of the rear udder region (715/2,135 observations with score > 0) and injured rear teats were also found frequently (694/2,652 observations with > 0 injured rear teats vs 179/2,156 observations with > 0 injured front teats). For other parameters, the prevalence of observed alterations was less than 2% (swelling in region of front/rear udder, claw length). Partial/missing front teats were also rarely found (17/2,154 observations with > 0 partial/missing front teat), whereas prevalence for partial/missing rear teats was higher (93/2,150). Injuries of the head, ears, neck, front udder region, vulva and legs, shoulder sores, vulval scarrings/missing parts, swellings of hind legs, infection of claws and lameness were observed in 2–10% of all assessments.

Risk factors for all parameters which were affected by both or either of the main treatment effects CP and PT, are shown in Table 4. The interaction of the two main effects was never significant and therefore excluded from the final model. Confinement period had an effect on two of the clinical welfare parameters, whereas PT was associated with eight parameters.

Effect of confinement period (CP)

Results for significant pair-wise comparisons between different CP are summarised in Table 5. The risk for developing injuries of the back was higher in CP 6-sows compared to CP 0- (OR 2.20; $P < 0.05$) and CP 3-sows (OR 1.51; $P < 0.05$). A higher risk for teat lesions was found in CP 4-sows than in all other CP (OR 1.41–1.60; $P < 0.001$).

Effect of pen-type (PT)

Odds ratios, confidence intervals and *P*-values of significant pair-wise comparisons can be found in Table 6. The risk for shoulder sores was more than 2.7 times higher ($P < 0.05$) for sows in K and T pens compared to S pens. Sows in P and K pens had higher odds ratios for injuries on the neck compared to at least two other pen-types (F vs P OR 3.64; $P < 0.05$; S vs P OR S-P 9.17; $P < 0.001$; T vs P OR 4.79; $P < 0.001$; S vs K OR 7.13; $P < 0.01$; T vs K OR 3.82; $P < 0.001$) and sows in F, K and P pens contracted more injuries on the back than in T pens (T vs F OR 2.50; $P < 0.05$; T vs K OR 3.12; $P < 0.05$; T vs P OR 5.10; $P < 0.001$). Odds ratios for back lesions were especially high in P pens. Additionally, high levels of injuries on the body side were found in P pens when compared to all other pens (F vs P OR 2.74; $P < 0.05$; K vs P OR 3.81; $P < 0.001$; S vs P OR 1.60; $P < 0.05$; T vs P OR 3.24; $P < 0.001$), but also in S pens when compared with K and T pens (K vs S OR 2.39; $P < 0.05$; T vs S OR 2.03; $P < 0.05$). There was a significant overall

Table 4 Odds ratios (OR), 95% confidence intervals (CI) and *P*-values of significant effects for parameters with significant effect(s) CP (confinement period) and/or PT (pen-type).

Parameter	Significant fixed effect of	OR	95% CI	*P*-value
Shoulder sore	BCS (thin) (0 vs 1)	4.158	1.801 to 9.600	< 0.001
	Assessment day (increase by 1)	2.022	1.725 to 2.370	< 0.001
	Parity (increase by 1)	1.215	1.061 to 1.391	0.005
	PT	*	*	0.037
Injuries neck	Assessment day (increase by 1)	1.308	1.109 to 1.542	0.001
	PT	*	*	< 0.001
Injuries back	Assessment day (increase by 1)	1.577	1.421 to 1.751	< 0.001
	Gilt/sow (0 vs 1)	3.40	1.934 to 5.978	< 0.001
	PT	*	*	< 0.001
	CP	*	*	0.021
Injuries body side	Assessment day (increase by 1)	1.434	1.265 to 1.625	< 0.001
	PT	*	*	0.004
Injuries udder	Assessment day (increase by 1)	1.780	1.608 to 1.970	< 0.001
	Gilt/sow (0 vs 1)	1.696	1.134 to 2.536	0.010
	PT	**	**	0.010
Changes claw horn	Assessment day (increase by 1)	1.548	1.338 to 1.791	< 0.001
	Gilt/sow (0 vs 1)	3.588	1.698 to 7.584	< 0.001
	PT	*	*	0.006
Lameness	Assessment day (increase by 1)	1.284	1.111 to 1.485	< 0.001
	Parity (increase by 1)	1.251	1.078 to 1.452	0.003
	PT	*	*	0.008
Number of injured teats	Assessment day (increase by 1)	1.165	1.084 to 1.252	< 0.001
	Litter size (increase by 1)	1.071	1.022 to 1.123	0.004
	PT	*	*	< 0.001
	CP	*	*	< 0.001

The higher the OR, the higher the odds of having a lesion, eg thin sows have a more than four times higher odds ratio of having shoulder sores than sows with normal BCS.
* OR, 95% CI and *P*-values shown for significant pair-wise comparisons in Tables 5 and 6.
** Pair-wise comparison not significant.

effect of the pen-type on injuries of the udder ($P < 0.05$), but pair-wise comparisons did not reveal significant differences between specific pen types. In pair-wise comparisons to F, S and T pens, rates of pathological changes of the claw horn of hind limbs were higher in P pens (F vs P OR 2.70; $P < 0.05$; S vs P OR 2.83; $P < 0.001$; T vs P OR 3.21; $P < 0.001$) as were odds ratios of lameness when compared with K, S and T pens (K vs P OR 2.98; $P < 0.001$; S vs P OR S-P 1.88; $P < 0.05$; T vs P OR 5.07; $P < 0.001$).

Other significant effects

The following factors affected parameters, which were also affected by CP and/or PT (see Table 4): low BCS was linked to increased odds ratios of shoulder sores (score 0–1 OR 4.16; $P < 0.001$). In general, the likelihood for alterations increased with time. The later the sows were assessed, the higher were the odds ratios (assessment day+1 OR ranging from number of injured teats 1.17 to shoulder sores 2.02, respectively, all $P < 0.001$). Increasing parity of the sow was associated with a higher risk of development of shoulder sores

Table 5 Contrasts represented by letters for parameters with significant effect confinement period (CP).

Parameter	CP				Sign, pair-wise comparison	OR	95% CI	*P*-value
	0	3	4	6				
Injuries back	a	a	ab	b	0–6	2.196	1.324 to 3.643	0.012
					3–6	1.512	0.953 to 2.399	0.010
Number of injured teats	a	a	b	a	0–4	1.600	1.257 to 2.037	< 0.001
					3–4	1.514	1.192 to 1.924	< 0.001
					6–4	1.410	1.124 to 1.769	< 0.001

CP 0-sows were not confined;
CP 3-sows were crated postpartum for 3 days;
Sows in CP 4 and CP 6 were crated from a day prior to expected farrowing until day 4 and 6 postpartum, respectively;
Alphabetical order of letters in columns 2–5 correlates with respective odds ratios.
Odds ratios (OR), 95% confidence intervals (CI) and *P*-values are shown for significant pair-wise comparisons.
The higher the OR is, the higher are the odds of having a lesion, eg CP 6-sows have 2.196 higher odds ratio of having shoulder sores than CP 0-sows and a 1.512 higher odds ratio than sows in CP 3.

(parity+1 OR 1.21, $P < 0.01$), injuries of the back (gilt/sow OR 3.40; $P < 0.001$) and the udder (gilt/sow OR 1.70; $P < 0.05$), changes of claw horn (gilt/sow OR 3.59; $P < 0.001$) and lameness (parity+1 OR 1.25; $P < 0.01$). Teat lesions increased with litter size (litter size+1 OR 1.07; $P < 0.01$).

Discussion

This study is one of the first to examine the effects of temporary crating of sows in differently designed farrowing pens. With 413 animals involved, it provides a solid database to reliably identify factors affecting sow health. In general, prevalence of pathological alterations are in the range of or lower than those reported in previous studies on sows housed in different environments (eg Bonde *et al* 2004; KilBride *et al* 2009b; Lambertz *et al* 2015). While previous studies commonly presented results from one farm, the current study included three different research farms, thereby improving external validity.

Nevertheless, some compromises had to be made between a balanced dataset, the requirements of the overarching project and statistical modelling. To save experimental time without losing information on piglet mortality during the first week of piglets' lives, farm C ran ten short batches. Hence, assessments during those batches were only conducted on days 1 and 2. During long batches, data were collected on farm C in contrast to the other farms on D4, in addition to D3. Although this led to an unbalanced dataset, it was carried out to gain information on the development of lesions until weaning. To save on degrees of freedom, to correctly model the covariance structure in our data and be able to use observations from all assessment days (including D4 on farm C), we fitted a random intercept and slope for sows. Therefore, pair-wise comparisons of different assessment days are not available and a linear increase of odds ratios with time is indicated for all parameters, as observations with score 1 at D1 were excluded from the analysis.

Confinement period

Confinement period had an effect only on skin injuries on the back and teat lesions. The low number of effects found supports a study from Lambertz *et al* (2015) who did not find differences in skin lesion prevalence in sows that were crated from farrowing until weaning, 14 or 7 days postpartum. In our study, we observed that back injuries increased the longer the sows were crated. The type of skin lesions investigated arose as a result of direct body contact with the physical environment. For example, gilts housed in gestation stalls showed higher skin lesion scores when entering the farrowing crates than gilts in pens (Boyle *et al* 2000). More specifically, Anil *et al* (2002) suggested that back lesions in sows in gestation stalls occur when the back is pressed forcefully against the bars on the sides of the stall during lateral recumbence because of inadequate stall width in relation to the height of the sow. In the present study, back injuries might have been caused by the lowest horizontal metal bars of the crates as well as the pins attached to these bars. The longer the sow is crated, the more lesions can therefore be expected. We found more than three times higher odds ratios in sows than in gilts. Sows' body dimensions increase with age (McGlone *et al* 2004; Moustsen *et al* 2011) and requirements for husbandry systems change along with body proportions so that previously appropriate constructions of housing might not fulfil the needs of older sows. It is important therefore that the crate is adjustable in width, length and height, and pen dimensions are aligned with the maximum size of sows.

With regard to teat lesions, prevalence was higher in the rear compared to the front region of the udder. This is in accordance with the work of Edwards and Lightfoot (1986) who noted that such lesions are caused by the back claws when the sow struggles to stand on perforated flooring. Teats can become damaged particularly during events of getting up and lying down when they can get trapped between (long) claws and the pen floor (Verhovsek *et al* 2007) or in

Table 6 Contrasts represented by letters for parameters with significant effect PT.

Parameter	PT					Sign, pair-wise comparison	OR	95% CI	*P*-value
	F	K	P	S	T				
Shoulder sore	ab	b	ab	a	b	S-K	2.755	1.126 to 6.740	0.025
						S-T	2.706	1.270 to 5.765	0.006
Injuries neck	ab	b	bc	a	a	F-P	3,644	1.585 to 8.377	0.014
						S-K	7.134	2.062 to 24.676	0.002
						S-P	9.174	2.711 to 34.810	< 0.001
						T-K	3.518	1.497 to 8.266	< 0.001
						T-P	4.790	1.932 to 11.879	< 0.001
Injuries back	bc	bc	c	ab	a	S-P	1.822	0.991 to 3.348	0.023
						T-F	2.488	1.408 to 4.395	0.015
						T-K	3.120	1.749 to 5.851	0.029
						T-P	5.099	2.597 to 10.011	< 0.001
Injuries body side	ab	ac	d	b	a	F-P	2.738	1.299 to 5.772	0.041
						K-P	3.810	1.612 to 9.003	< 0.001
						K-S	2.388	1.192 to 4.786	0.038
						S-P	1.596	0.761 to 3.346	0.041
						T-P	3.242	1.527 to 6.882	< 0.001
						T-S	2.032	1.120 to 3.720	0.038
Injuries udder	a	a	a	a	a	*	*	*	*
Changes claw horn	ab	bc	c	ab	a	F-P	2.696	1.698 to 7.584	0.050
						S-P	2.834	1.297 to 6.193	< 0.001
						T-K	2.227	1.133 to 4.375	< 0.001
						T-P	3.209	1.508 to 6.829	< 0.001
Lameness	ab	a	b	a	a	K-P	2.984	1.171 to 7.604	< 0.001
						S-P	1.880	0.833 to 4.243	0.012
						T-P	5.074	2.038 to 12.630	< 0.001
Number of injured teats	b	a	a	a	ab	K-F	1.567	1.192 to 2.059	0.012
						P-F	1.611	1.153 to 2.249	0.041
						S-F	1.669	1.285 to 2.168	0.001

Pen-types (PT): F: Flügel, K: Knick, P: Pro Dromi, S: SWAP, T: Trapez.
Alphabetical order of letters in columns 2–6 correlates with respective odds ratios.
Odds ratios (OR), 95% confidence intervals (CI) and *P*-values are shown for significant pair-wise comparisons. The higher the OR, the higher the odds of having a lesion, eg sows in PT K have 2.755 higher odds ratio of having shoulder sores than sows in PT S.
* Pair-wise comparison not significant.

between slats. Therefore, type of flooring together with claw length as well as slat width play an important role in the development of teat lesions (Edwards & Lightfoot 1986). Crated sows cannot choose the type of flooring they stand or lie on, which might be detrimental for udder health, especially during postural changes. Thus, it seems reasonable to assume that the likelihood of teat injuries would increase with confinement duration. In this respect, it is important to consider that particularly during the nest-building phase, behaviour of sows confined one day before expected farrowing may differ from that of loose-housed sows or sows crated immediately following farrowing (Hansen *et al* 2017). Crated sows perform more postural changes (Damm *et al* 2003) which might lead to teat damage. That would explain why odds ratios of teat lesions were significantly higher in CP 4- than in CP 3-sows, but it does not explain why a significantly greater number of teat lesions was also found in CP 4- than CP 6-sows. The reasons why this type of lesion was explicitly pronounced in CP 4-sows compared to all other confinement periods cannot be explained from the present study.

The observation that the number of injured teats increases with litter size is in accordance with previous findings (Lewis *et al* 2005; Norring *et al* 2006). In large litters, the amount of milk per piglet is lower than in small ones (Auldist *et al* 1998) and therefore piglets in large litters fight more over teats, leading to more udder damage (Milligan *et al* 2001; Baxter *et al* 2013; Rutherford *et al* 2013).

Overall, the few effects found regarding period of confinement can be explained by comparatively small differences in duration. Furthermore, as the actual farrowing date often did not match exactly with the expected date, there would be an overlap between the different confinement periods so that, for example, a sow which was crated according to CP 4 could be crated for a longer period of time than a sow in CP 6. From a scientific perspective, it would have been interesting to have examined the effect of actual duration of crating as a continuous variable on sow health. For future studies it would be useful to assess sows more frequently to be able to make more specific statements regarding the development of lesions. However, our aim was to identify a strategy for temporary confinement and to test different pen systems that would work for a whole range of sows independent of breed, age, size, behavioural features and previous experiences. Therefore, we preferred a large sample size of animals over more frequent examinations on one sow and defined CP as a categorical variable.

Type of pen

For PT, more significant effects were found than for CP. This may be explained by the fact that all sows were loose-housed longer than they were crated so that lesions due to overall pen design and equipment had more time to evolve than those caused by the crate.

Shoulder sores can trigger pain (Dahl-Pedersen *et al* 2013) and subsequently also modify lying behaviour (Larsen *et al* 2015). They are multifactorial in nature, mainly caused by the interaction of body condition, lying behaviour and flooring (Bonde *et al* 2004; Cleveland-Nielsen *et al* 2004; Rolandsdotter *et al* 2009). The main mechanism involved is thought to be external pressure against the spine of the shoulder blade, which is covered only by skin and subcutaneous fat (Jensen & Svendsen 2006; Herskin *et al* 2011). In the present study, prevalence of shoulder sores was comparable with previous findings: 10% prevalence among sows in 86 herds kept in- or outdoors (KilBride *et al* 2009b); 34% among sows in farrowing crates (Zurbrigg 2006); 12% in sows in farrowing crates (Bonde *et al* 2004). Solid floors provide more surface area to support the tuber of the scapula than slatted floors and therefore reduce pressure and shearing forces applied to this region (Zurbrigg 2006). This may explain why sows in PT S with the highest ratio of solid floor of all pens were less likely to develop shoulder lesions than sows in PT K and T. In the latter two pens, high proportions of slatted floor together with certain behavioural traits, especially lying behaviour during the time the sows were kept loose, might have caused more shoulder sores. However, conclusions regarding lesion-inducing structures, such as flooring of respective pens are speculative, as pen-types as a whole were compared and thus conclusions of the effects of particular components of the pen structures cannot be drawn. Thin sows were more likely to develop shoulder sores than sows with a normal or high BCS. This finding is in agreement with former studies (Davies *et al* 1997; Bonde *et al* 2004; Salak-Johnson *et al* 2007). It can be explained by the fact that a lower BCS is negatively correlated with the thickness of soft tissue covering the tuber scapulae, which can be regarded as a determinant of the risk of developing shoulder lesions (Davies *et al* 1997).

Parity also had an impact on decubital ulcers. As already observed by Rosendahl and Nielsen (2004) and Zurbrigg (2006), in sows, the risk of developing a lesion increases with age. Older sows tend to be larger and heavier than younger ones and would alter their posture less often, especially when space allowance is restricted (Davies *et al* 1996, 1997; McGlone *et al* 2004). Higher bodyweight as well as longer duration of uninterrupted lateral recumbency means more pressure on the skin over the scapula (Davies *et al* 1996, 1997). At the same time, decubital ulcers that heal during the gestation period might provoke an increased risk of developing a new lesion during the next parity (Davies *et al* 1996; Rosendahl & Nielsen 2004). Moreover, compared with the other modelled parameters, assessment day had the highest impact on decubital ulcers, with the risk of developing a shoulder sore increasing more than twice from one assessment day to the next. This finding might be linked to long lying bouts, especially during early lactation and therefore persistent pressure on the shoulder and decreasing body condition score and bodyweight until weaning (Zurbrigg 2006).

In pens K and P an unfavourable arrangement of the area in front of the trough could be the explanation for high odds ratios as regards neck injuries. In K, the distance from the trough to the floor was only as high as the rostral part of a sow's head so that she could get stuck between these two elements and the first pin of the crate, resulting in abrasive lesions of the neck that emerged from postural changes during feeding. Similarly, sows in P could get stuck with their heads between the floor and brackets mounted at neck height to the lowest bar of the crate.

Both confined and free sows were able to use the crate in the same way as farrowing rails and sloping walls are used by free sows as supportive surfaces to transition between standing and lying (Blackshaw & Halgelsø 1990; Damm *et al* 2006). Regarding the development of back lesions, this might explain the lack of effect of an interaction of CP and PT despite the fact that both main effects were significant. The high likelihood of back lesions found in PT P might be due to forceful pressing against the bars when lying laterally (Anil *et al* 2002) or rubbing during lying-down or standing-up movements. The distance between the lowest bar of the crate and the floor was highest in pen-type T (40 cm) and smallest in P (30 cm), which might explain why there was five times the odds ratios of back lesions in P.

S and P were the two pen-types with higher odds ratios for injuries of the body side compared to at least two other pens. At the same time, these two pens were the only that had sloping walls, which may be suggestive of sloping wall edges having some sort of impact on the development of such lesions.

Lameness is one of the main reasons for culling of sows in intensive management (for a review, see Heinonen *et al* 2013). It can have a major impact on health and welfare of sows and, at the same time, causes considerable economic loss (Anil *et al* 2005). Mean prevalence in conventional herds has been reported to range between 9.7 (Pluym *et al* 2011) and 24.3% (Knage-Rasmussen *et al* 2014) in gestating sows and Bonde *et al* (2004) observed 15% lame sows kept in farrowing crates. We found 8.0% lame sows across all farms and assessment days. However, lame sows with a score of 2 might be underrepresented by these numbers since severely lame sows were immediately excluded from the trial and prevalences among gestating and lactating sows could have been considerably higher (cf Zurbrigg & Blackwell 2006: 18% of gestating sows lame with 4.9% severely lame animals).

Lameness occurred in P pens in many cases together with changes of claw horn, which have been described as one potential reason for lameness (Dewey *et al* 1993). Slatted floors can be slippery (Edwards & Lightfoot 1986), leading to increased prevalence of limb lesions, including claw abnormalities and subsequent lameness (Heinonen *et al* 2006; Anil *et al* 2007; KilBride *et al* 2009a). The proportion of slatted floor was high in P pens and, although not scientifically confirmed, the plastic floor was reported by the farm staff to be slippery. Nevertheless, a potential effect of farm must be taken into account as pen-type P was only available on farm C and was also used during routine farrowing events. This also raises the question of whether findings might have been impacted by pathological alterations from earlier production cycles that were initially subclinical (when the sows were moved to the farrowing unit for the experiment) but subsequently became clinical. Especially in the two parameters 'lameness' and 'changes of claw horn', the effect of 'farm' might have had an impact on the results as farm C was affected by a lameness problem caused by wall cracks of the claw horn during the entire experimental period.

More damaged teats were observed in F than in K, P and S pens. This can be attributed to the high ratio of slatted floor in the back of the pen in combination with low space provision. These pen characteristics might have been relevant for lesion development when the sows were kept loose. Perforated flooring is considered to cause more teat lesions than a solid floor (Edwards & Lightfoot 1986). Low space provision in the back area of the pen, which seemed to have been preferred by the sows when they were not crated, in combination with further restriction of space caused by three farrowing rails might have led to modified behaviour with a detrimental effect on the udder. According to Curtis *et al* (1989), getting-up and lying-down events in a sow of 250 kg live weight require an area of at least 2.20 × 0.86 m (length × width). Compared to these conditions, the width of the overall F pen (2.10 m without taking farrowing rails into account) is too small.

Effects of pen-type were diverse and were not restricted to one particular type. However, some of the health-related alterations we found have major significance for animal welfare, as the European Food Safety Authority (2007) lists claw damage, shoulder lesions and teat damage as considerable welfare risks in farrowing sows. They can cause pain and, in the long term, lead to reduced productivity and premature culling. Except for S, all of the tested pens led to increased likelihood of alterations of these parameters. Sows in PT P were prone to claw horn lesions, those in K and T had comparably high odds for shoulder sores, whereas PT F led to more injured teats. Therefore, regarding the health-related parameters of sows investigated here, PT S can be recommended. Additionally, pen elements in PT F, K and T should be adapted to reduce lesions. In PT P, a complete redesign of the pen might be necessary as several elements, such as the floor and crate, are dysfunctional. As already discussed in earlier studies, flooring and structuring are inseparably linked to the development of lesions in sows kept in farrowing systems (Edwards & Lightfoot 1986; Baxter *et al* 2011). Features such as pen dimensions and space allowance and elements that restrict movement (bars, pins, farrowing rails) require particular attention. Future studies should take into account these findings and investigate the development of lesions on the basis of genuine crating times as opposed to predefined confinement periods. Also, different structural elements of farrowing pens (eg flooring) that might cause lesions in sows should be tested separately from other, potentially harmful pen elements.

Animal welfare implications

This study is one of the first to investigate the impact of periparturient temporary crating on selected parameters of sow health. Additionally, it compared different types of farrowing pens which allowed the possibility of crating the sow. The results pinpoint specific regions of the body that are particularly susceptible to injuries caused by the farrowing crate as well as structures of farrowing pens that lead potentially to lesions. Therefore, it provides important information for legislative authorities as well as housing construction companies and farmers for decision-making and management.

Conclusion

This study revealed that the length of temporary crating of the sow around parturition affects a number of specific health parameters. If confinement for a few days is applied then attention should focus on crate measurements in relation to individual sow dimensions and adjustability of the crate in terms of width, length and height. Nevertheless, appropriate dimensions in relation to individual sow measurements and lesion-causing features of farrowing accommodations (eg flooring, bars, rails, pins) have also to be considered when the sow can move freely in a pen, as our results confirm the effect of pen-type to be even more important for sow well-being than the duration of temporary confinement.

Acknowledgements

Project Pro-SAU was funded by former Bundesministerium für Gesundheit und Frauen (BMGF, Federal Ministry for Health and Women) and former Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW, Federal Ministry of Agriculture, Forestry, Environment and Water Management, research project 100986 BMLFUW-LE.1.3.2/0086-II/1/2013). The authors would like to thank everyone involved in the project, including farm staff, data collectors and collaboration partners for excellent and unique co-operation. The authors have no conflict of interest to declare.

References

Anil L, Anil SS and Deen J 2002 Evaluation of the relationship between injuries and size of gestation stalls relative to size of sows. *Journal of American Veterinary Medical Association 221*: 834-836. https://doi.org/10.2460/javma.2002.221.834

Anil SS, Anil L and Deen J 2005 Evaluation of patterns of removal and associations among culling because of lameness and sow productivity traits in swine breeding herds. *Journal of American Veterinary Medical Association 226*: 956-961. https://doi.org/10.2460/javma.2005.226.956

Anil SS, Anil L and Deen J 2007 Factors associated with claw lesions in gestating sows. *Journal of Swine Health and Production 15*: 78-83

Auldist D, Morrish L, Eason P and King R 1998 The influence of litter size on milk production of sows. *Animal Science 67*: 333-337. https://doi.org/10.1017/S1357729800010109

Barton K 2017 *MuMIn: Multi-Model Inference. R package version 1.40.0.* https://CRAN.R-project.org/package=MuMIn

Bates D, Maechler. M, Bolker B, and Walker S 2015 Fitting linear mixed-effects models using [lme4]. *Journal of Statistical Software 67*: 1-48. https://doi.org/10.18637/jss.v067.i01

Baxter EM, Lawrence AB and Edwards SA 2011 Alternative farrowing systems: design criteria for farrowing systems based on the biological needs of sows and piglets. *Animal 5*: 580-600. https://doi.org/10.1017/S1751731110002272

Baxter EM, Rutherford KMD, D'Eath RB, Arnott G, Turner SP, Sandøe P, Moustsen VA, Thorup F, Edwards SA and Lawrence AB 2013 The welfare implications of large litter size in the domestic pig II: management factors. *Animal Welfare 22*: 219-238. https://doi.org/10.7120/09627286.22.2.219

Blackshaw JK and Halgelsø 1990 Getting-up and lying-down behaviours of loose-housed sows and social contacts between sows and piglets during day 1 and day 8 after parturition. *Applied Animal Behaviour Science 25*: 61-70. https://doi.org/10.1016/0168-1591(90)90070-T

BMG 2012 *Verordnung des Bundesministers für Gesundheit, mit der die 1. Tierhaltungsverordnung geändert wird, BGBl. II Nr 61/2012 vom 09.03.2012*. https://www.ris.bka.gv.at/eli/bgbl/II/2012/61/20120309

BMGF 2004 *Verordnung der Bundesministerin für Gesundheit und Frauen über die Mindestanforderungen für die Haltung von Pferden und Pferdeartigen, Schweinen, Rindern, Schafen, Ziegen, Schalenwild, Lamas, Kaninchen, Hausgeflügel, Straußen und Nutzfischen (1. Tierhaltungsverordnung) vom 17.12.2004*. https://www.ris.bka.gv.at /eli/bgbl/II/2004/485/20041217

BMWF 2012 *Bundesgesetz, mit dem ein Tierversuchsgesetz 2012 erlassen wird sowie das Arzneimittelgesetz, das Biozid-Produkte-Gesetz, das Futtermittelgesetz 1999, das Gentechnikgesetz sowie das Tierschutzgesetz geändert werden (Tierversuchsrechtsänderungsgesetz – TVRÄG), BGBl. I Nr 114/2012 vom 28.12.2012*. https://www.ris.bka.gv.at/eli/bgbl/I /2012/114/20121228

Bonde M, Rousing T, Badsberg JH and Sørensen JT 2004 Associations between lying-down behaviour problems and body condition, limb disorders and skin lesions of lactating sows housed in farrowing crates in commercial sow herds. *Livestock Production Science 87*: 179-187. https://doi.org/10.1016/j.livprodsci.2003.08.005

Boyle LA, Leonard FC, Lynch PB and Brophy P 2000 Influence of housing system during gestation on the behaviour and welfare of gilts in farrowing crates. *Animal Science 71*: 561-570. https://doi.org/10.1017/S1357729800055302

Boyle LA, Leonard FC, Lynch PB and Brophy P 2002 Effect of gestation housing on behaviour and skin lesions of sows in farrowing crates. *Applied Animal Behaviour Science 76*: 119-134. https://doi.org/10.1016/S0168-1591(01)00211-8

Cleveland-Nielsen A, Bækbo P and Ersbøll AK 2004 Herd-related risk factors for decubital ulcers present at post-mortem meat-inspection of Danish sows. *Preventative Veterinary Medicine 64*: 113-122. https://doi.org/10.1016/j.prevetmed.2004.05.004

Cronin GM, Smith JA, Hodge FM and Hemsworth PH 1994 The behaviour of primiparous sows around farrowing in response to restraint and straw bedding. *Applied Animal Behaviour Science 39*: 269-280. https://doi.org/10.1016/0168-1591(94)90162-7

Curtis SE, Hurst RJ, Gonyou HW, Jensen AH and Muehling AJ 1989 The physical space requirement of the sow. *Journal of Animal Science 67*: 1242-1248. https://doi.org/10.2527/jas1989.6751242x

Dahl-Pedersen K, Bonde MK, Herskin MS, Jensen KH, Kaiser M and Jensen HE 2013 Pathogenesis and pathology of shoulder ulcerations in sows with special reference to peripheral nerves and behavioural responses to palpation. *The Veterinary Journal 198*: 666-671. https://doi.org/10.1016/j.tvjl.2013.09.059

Damm BI, Lisborg L, Vestergaard KS and Vanicek J 2003 Nest-building, behavioural disturbances and heart rate in farrowing sows kept in crates and Schmid pens. *Livestock Production Science 80*: 175-187. https://doi.org/10.1016/S0301-6226(02)00186-0

Damm BI, Moustsen V, Jørgensen E, Pedersen LJ, Heiskanen T and Forkman B 2006 Sow preferences for walls to lean against when lying down. *Applied Animal Behaviour Science 99*: 53-63. https://doi.org/10.1016/j.applanim.2005.09.014

Davies PR, Morrow WEM, Miller DC and Deen J 1996 Epidemiologic study of decubital ulcers in sows. *Journal of American Veterinary Medical Association 208*: 1058-1062

Davies PR, Morrow WEM, Rountree WG and Miller DC 1997 Epidemiologic evaluation of decubital ulcers in farrowing sows. *Journal of American Veterinary Medical Association 210*: 1173-1178

Dewey CE, Friendship RM and Wilson MR 1993 Clinical and postmortem examination of sows culled for lameness. *The Canadian Veterinary Journal 34*: 555-556

Dyck GW and Swierstra EE 1987 Causes of piglet death from birth to weaning. *Canadian Journal of Animal Science 67*: 543-547. https://doi.org/10.4141/cjas87-053

Edwards S and Fraser D 1997 Housing systems for farrowing and lactation. *Pig Journal 39*: 77-89

Edwards SA and Lightfoot AL 1986 The effect of floor type in farrowing pens on pig injury II. Leg and teat damage of sows. *British Veterinary Journal 142*: 441-445. https://doi.org/10.1016/0007-1935(86)90045-X

EFSA 2007 Animal health and welfare aspects of different housing and husbandry systems for adult breeding boars, pregnant, farrowing sows and unweaned piglets - Scientific Opinion of the Panel on Animal Health and Welfare. *EFSA Journal 5*: 572. https://doi.org/10.2903/j.efsa.2007.572

Fox J and Weisberg S 2011 *An [R] Companion to Applied Regression*. Sage: Thousand Oaks, CA, USA

Friendly M 2017 *vcdExtra: 'vcd' Extensions and Additions. R package version 0.7-1.* https://CRAN.R-project.org/package=vcdExtra

Hales J, Moustsen VA, Nielsen MBF and Hansen CF 2014 Higher preweaning mortality in free farrowing pens compared with farrowing crates in three commercial pig farms. *Animal 8*: 113-120. https://doi.org/10.1017/S1751731113001869

Hales J, Moustsen VA, Nielsen MBF and Hansen CF 2015 Temporary confinement of loose-housed hyperprolific sows reduces piglet mortality. *Journal of Animal Science 93:* 4079-4088. https://doi.org/10.2527/jas.2015-8973

Hansen CF, Hales J, Weber PM, Edwards SA and Moustsen VA 2017 Confinement of sows 24 h before expected farrowing affects the performance of nest building behaviours but not progress of parturition. *Applied Animal Behaviour Science 188*: 1-8. https://doi.org/10.1016/j.applanim.2017.01.003

Harris MJ and Gonyou HW 1998 Increasing available space in a farrowing crate does not facilitate postural changes or maternal responses in gilts. *Applied Animal Behaviour Science 59*: 285-296. https://doi.org/10.1016/S0168-1591(98)00142-7

Hartig F 2016 *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.1.4.* https://cran.r-project.org/web/packages/DHARMa

Heidinger B, Stinglmayr J, Maschat K, Oberer M, Blumauer E, Kuchling S, Leeb C, Hatzmann E, Zentner E, Hochfellner L, Laubichler C, Dolezal M, Schwarz L, Mösenbacher-Molterer I, Vockenhuber D and Baumgartner J 2017 *Evaluierung von neuen Abferkelbuchten mit Bewegungsmöglichkeit für die Sau, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft*. https://www.dafne.at/dafne_plus_homepage/index.php?section=dafneplus&content=result&come_from=homepage&&project_id=3316. [Title translation: Evaluation of novel farrowing systems with the possibility for the sow to move]

Heinonen M, Oravainen J, Orro T, Seppä-Lassila L, Ala-Kurikka E, Virolainen J, Tast A and Peltoniemi OAT 2006 Lameness and fertility of sows and gilts in randomly selected loose-housed herds in Finland. *Veterinary Record 159*: 383. https://doi.org/10.1136/vr.159.12.383

Heinonen M, Peltoniemi O and Valros A 2013 Impact of lameness and claw lesions in sows on welfare, health and production. *Livestock Science 156*: 2-9. https://doi.org/10.1016/j.livsci.2013.06.002

Herskin MS, Bonde MK, Jørgensen E and Jensen KH 2011 Decubital shoulder ulcers in sows: a review of classification, pain and welfare consequences. *Animal 5*: 757-766. https://doi.org/10.1017/S175173111000203X

Holm S 1979 A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics 6*: 65-70

Jarvis S, Van der Vegt BJ, Lawrence AB, McLean KA, Deans LA, Chirnside J and Calvert SK 2001 The effect of parity and environmental restriction on behavioural and physiological responses of pre-parturient pigs. *Applied Animal Behaviour Science 71*: 203-216. https://doi.org/10.1016/S0168-1591(00)00183-0

Jensen HE and Svendsen O 2006 Skuldersår hos søer - Patogenese, graduering og komparative aspekter. *Dansk Veterinærtidsskrift 89*: 14-16. [Title translation: Shoulder ulcers in sows - pathogenesis, scoring and comparative aspects]

Kielland C, Wisløff H, Valheim M, Fauske AK, Reksen O and Framstad T 2018 Preweaning mortality in piglets in loose-housed herds: etiology and prevalence. *Animal 12*: 1950-1957. https://doi.org/10.1017/S1751731117003536

KilBride A, Gillman C, Ossent P and Green L 2009a Impact of flooring on the health and welfare of pigs. *In Practice 31*: 390-395. https://doi.org/10.1136/inpract.31.8.390

KilBride AL, Gillman CE and Green LE 2009b A cross sectional study of the prevalence, risk factors and population attributable fractions for limb and body lesions in lactating sows on commercial farms in England. *BMC Veterinary Research 5*: 30. https://doi.org/10.1186/1746-6148-5-30

Kilbride AL, Mendl M, Statham P, Held S, Harris M, Cooper S and Green LE 2012 A cohort study of preweaning piglet mortality and farrowing accommodation on 112 commercial pig farms in England. *Preventative Veterinary Medicine 104*: 281-291. https://doi.org/10.1016/j.prevetmed.2011.11.011

Knage-Rasmussen KM, Houe H, Rousing T and Sørensen JT 2014 Herd- and sow-related risk factors for lameness in organic and conventional sow herds. *Animal 8*: 121-127. https://doi.org/10.1017/S1751731113001900

Lambertz C, Petig M, Elkmann A and Gauly M 2015 Confinement of sows for different periods during lactation: effects on behaviour and lesions of sows and performance of piglets. *Animal 9*: 1373-1378. https://doi.org/10.1017/S1751731115000889

Larsen T, Kaiser M and Herskin MS 2015 Does the presence of shoulder ulcers affect the behaviour of sows? *Research in Veterinary Science 98*: 19-24. https://doi.org/10.1016/ j.rvsc.2014.11.001

Lawrence AB, Petherick JC, McLean KA, Deans LA, Chirnside J, Gaughan A, Clutton E and Terlouw EMC 1994 The effect of environment on behaviour, plasma cortisol and prolactin in parturient sows. *Applied Animal Behaviour Science 39*: 313-330. https://doi.org/10.1016/0168-1591(94)90165-1

Leeb C, Bernardi F and Winckler C 2010 *Einführung und Monitoring von 'BetriebsEntwicklungsPlänen (BEP) Tiergesundheit und Wohlbefinden' in österreichischen Bioschweinebetrieben. Endbericht zum Forschungsprojekt 100188*. Eigenverlag: Vienna, Austria. [Title translation: Implementation and monitoring of farm development plans (BEP) animal health and welfare in Austrian organic pig farms]

Lefcheck JS 2016 PiecewiseSEM: Piecewise structural equation modeling in R for ecology, evolution, and systematics. *Methods in Ecology and Evolution 7*: 573-579. https://doi.org/10.1111/2041-210X.12512

Lesnoff M and Lancelot R 2012 *aod: Analysis of overdispersed data, R package version 1.3*. http://cran.r-project.org/package=aod

Lewis E, Boyle LA, Lynch PB, Brophy P and O'Doherty JV 2005 The effect of two teeth resection procedures on the welfare of piglets in farrowing crates, part 1. *Applied Animal Behaviour Science 90*: 233-249. https://doi.org/10.1016/j.applanim.2004.08.022

Marchant J, Broom D and Corning S 2001 The influence of sow behaviour on piglet mortality due to crushing in an open farrowing system. *Animal Science 72*: 19-28. https://doi.org/10.1017/S135772980005551X

Marchant JN, Rudd AR, Mendl MT, Broom DM, Meredith MJ, Corning S and Simmins PH 2000 Timing and causes of piglet mortality in alternative and conventional farrowing systems. *The Veterinary Record 147*: 209-214. https://doi.org/10.1136/vr.147.8.209

McGlone JJ, Vines B, Rudine AC and DuBois P 2004 The physical size of gestating sows. *Journal of Animal Science 82*: 2421-2427. https://doi.org/10.2527/2004.8282421x

Meyer D, Zeileis A and Hornik K 2006 The Strucplot Framework: Visualizing multi-way contingency tables with vcd. *Journal of Statistical Software 17*: 1-48. https://doi.org/10.18637/jss.v017.i03

Meyer D, Zeileis A, and Hornik K 2017 *vcd: Visualizing Categorical Data. R package version 1.4-4*. https://cran.r-project.org/web/packages/vcd/

Milligan BN, Fraser D and Kramer DL 2001 Birth weight variation in the domestic pig: effects on offspring survival, weight gain and suckling behaviour. *Applied Animal Behaviour Science 73*: 179-191. https://doi.org/10.1016/S0168-1591(01)00136-8

Moustsen VA, Hales J, Lahrmann HP, Weber PM and Hansen CF 2013 Confinement of lactating sows in crates for 4 days after farrowing reduces piglet mortality. *Animal 7*: 648-654. https://doi.org/10.1017/S1751731112002170

Moustsen VA, Lahrmann HP and D'Eath RB 2011 Relationship between size and age of modern hyper-prolific crossbred sows. *Livestock Science 141*: 272-275. https://doi.org/10.1016/j.livsci.2011.06.008

Nicolaisen T, Lühken E, Volkmann N, Rohn K, Kemper N and Fels M 2019 The effect of sows' and piglets' behaviour on piglet crushing patterns in two different farrowing pen systems. *Animals 9*: 538. https://doi.org/10.3390/ani9080538

Norring M, Valros A, Munksgaard L, Puumala M, Kaustell KO and Saloniemi H 2006 The development of skin, claw and teat lesions in sows and piglets in farrowing crates with two concrete flooring materials. *Acta Agriculturae Scandinavica, Section A — Animal Science 56*: 148-154. https://doi.org/10.1080/09064700701285065

Olsson A-C, Botermans J and Englund J-E 2018 Piglet mortality. A parallel comparison between loose-housed and temporarily confined farrowing sows in the same herd. *Acta Agriculturae Scandinavica, Section A — Animal Science 68*: 52-62. https://doi.org/10.1080/09064702.2018.1561934

Pluym L, Van Nuffel A, Dewulf J, Cools A, Vangroenweghe F, Van Hoorebeke S and Maes D 2011 Prevalence and risk factors of claw lesions and lameness in pregnant sows in two types of group housing. *Veterinarni Medicina (Praha) 56*: 101-109. https://doi.org/10.17221/3159-VETMED

R Core Team 2013 *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria

Rolandsdotter E, Westin R and Algers B 2009 Maximum lying bout duration affects the occurrence of shoulder lesions in sows. *Acta Agriculturae Scandinavica, Section A — Animal Science 51*: 1-7. https://doi.org/10.1186/1751-0147-51-44

Rosendahl T and Nielsen JP 2004 Risk factors for the development of decubital ulcers over the scapula in sows. *Proceedings of the 18th IPVS Congress* pp 717. 27 June-1 July 2004, Hamburg, Germany

Rutherford KMD, Baxter EM, D'Eath RB, Turner SP, Arnott G, Roehe R, Ask B, Sandøe P, Moustsen VA, Thorup F, Edwards SA, Berg P and Lawrence AB 2013 The welfare implications of large litter size in the domestic pig I: biological factors. *Animal Welfare 22*: 199-218. https://doi.org/10.7120/09627286.22.2.199

Salak-Johnson JL, Niekamp SR, Rodriguez-Zas SL, Ellis M and Curtis SE 2007 Space allowance for dry, pregnant sows in pens: Body condition, skin lesions, and performance 1. *Journal of Animal Science 85*: 1758-1769. https://doi.org/10.2527/jas.2006-510

Sarkar D 2008 *Lattice: Multivariate Data Visualization with R*. Springer: New York, USA. https://doi.org/10.1007/978-0-387-75969-2

Troxler J and Weber R 1988 Anwendung ethologischer Erkenntnisse bei der Prüfung von Stalleinrichtungen für Schweine. *Aktuelle Arbeiten zur artgemäßen Tierhaltung* pp 142-149. 17-19 November 1988, Freiburg/Breisgau, Germany. KBTL: Darmstadt, Germany. [Title translation: Application of ethological findings in the testing of housing facilities for pigs]

Venables WN and Ripley BD 2002 *Modern Applied Statistics with S*. Springer: New York, USA. https://doi.org/10.1007/978-0-387-21706-2

Verhovsek D, Troxler J and Baumgartner J 2007 Peripartal behaviour and teat lesions of sows in farrowing crates and in a loose-housing system. *Animal Welfare 16*: 273-276

Weber R, Keil N, Fehr M and Horat R 2007 Piglet mortality on farms using farrowing systems with or without crates. *Animal Welfare 16*: 277-279

Welfare Quality® 2009 *Assessment protocol for pigs*. Welfare Quality® Consortium: Lelystad, The Netherlands

Wickham H 2009 *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag: New York, USA. https://doi.org/10.1007/978-0-387-98141-3

Zurbrigg K 2006 Sow shoulder lesions: Risk factors and treatment effects on an Ontario farm. *Journal of Animal Science 84*: 2509-2514. https://doi.org/10.2527/jas.2005-713

Zurbrigg K and Blackwell T 2006 Injuries, lameness, and cleanliness of sows in four group-housing gestation facilities in Ontario. *Journal of Swine Health and Production 14*: 202-206