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## QUANTIFICATION AND REPEATED MEASUREMENTS OF CONFORMATION TRAITS IN REPLACEMENT FEMALES TO OPTIMIZE SOW LONGEVITY

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QUANTIFICATION AND REPEATED MEASUREMENTS OF CONFORMATION  
TRAITS IN REPLACEMENT FEMALES TO OPTIMIZE SOW LONGEVITY

by

Melanie D. Trenhaile Grannemann

A DISSERTATION

Presented to the Faculty of

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In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Animal Science

(Breeding and Genetics)

Under the Supervision of Professor Benny E. Mote

Lincoln, Nebraska

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QUANTIFICATION AND REPEATED MEASUREMENTS OF CONFORMATION  
TRAITS IN REPLACEMENT FEMALES TO OPTIMIZE SOW LONGEVITY

Melanie Dawn Trenhaile Grannemann, Ph.D.

University of Nebraska, 2021

Advisor: Benny E. Mote

The objectives were to 1) assess the reliability of objective conformation trait measurements between evaluators, 2) evaluate effects of dietary energy and lysine during development and housing system during first gestation on longevity, reproductive performance, and conformation, 3) characterize conformation changes throughout life, 4) identify phenotypic associations between conformation and longevity, 5) estimate heritability of conformation traits, and 6) assess genetic relationships between conformation traits measured throughout life in sows. Sows ( $n = 622$ ) were fed a standard, energy restricted, or standard energy with increased lysine diet during gilt development and housed in either a group pen or stall during first gestation. Conformation traits, including five body size traits, knee, hock, and pastern angles, rump slope, and foot directional position, were objectively measured at 16 time points between 112 days of age and parity 4 weaning. Three types of foot lesions were evaluated at the latter 14 time points. Intra-class correlations demonstrated objectively measured conformation traits are reliable between evaluators; they also improve consistency, encompass the full range of trait phenotypic values, and allow identification of small conformational differences. Energy restriction during development had favorable effects

on performance, including increased feed intake and decreased body condition loss during lactation. Pen housing had detrimental effects on conformation, including steeper rumps and pasterns, more “toed out” rear feet, and increased foot lesion severity. Changes over time were observed for all conformation traits. Body size increased while knee and pastern angles decreased. A pattern of change following the gestation cycle was observed for several traits. Associations were identified between sow longevity and conformation traits, including body depth, height, knee angle, rear foot directional position, heel-sole cracks, and total rear foot lesions. Objectively measured conformation traits and foot lesions were heritable (median  $h^2 = 0.11$  to  $0.37$ ). Genetic correlations between body size traits, knee, hock, and pastern angles, and rump slope evaluated throughout life suggest these traits have the same genetic determinism from first to fourth gestation.

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## **CHAPTER 1: LITERATURE REVIEW**

### **1.1 Relationship Between Conformation Traits and Sow Longevity**

Sow longevity is of high economic importance to the swine industry. However, sow mortality and culling rates have been increasing in the last two decades (Supakorn et al., 2019). A sow must produce three parities to cover her development and maintenance costs and become profitable (Stalder et al., 2003; Mote et al., 2008). In addition, reproductive performance, particularly litter size, does not reach its peak until parities 3 to 6 (English et al., 1978, as cited by Friendship et al., 1986). Therefore, culling or death prior to this point results in lower farm productivity and profitability.

Lameness associated with structural unsoundness is the second most common reason for early culling (culling for any reason other than age) in the United States (Mote et al., 2008) and Mexico (Segura-Correa et al., 2011), accounting for 22.3% of all removals in the three Midwestern commercial swine farms analyzed by Mote et al. (2008) and 15.5% of all removals in three commercial farms in Mexico (Segura-Correa et al., 2011). Lameness also accounted for 22.5% of sow removals on four farms in Southern China (Zhao et al., 2015). In Sweden, lameness ranked fourth in causes of sow removal (Engblom et al., 2007). This difference is likely due to differences in management and housing in Europe compared to North America and Asia. Straw bedding, a requirement for sows in Sweden, may reduce lameness, but mastitis and other udder problems are a much larger contributor to culling in Sweden than the United States and Canada (Engblom et al., 2007). While actual removal rates may be lower, the prevalence of lameness is variable between European countries and studies. Eight farms in Belgium had a lameness rate of 9.7% on average (Pluym et al., 2011) while 15.0% of



sows on ten farms in Denmark were lame (Bonde et al., 2004). In 88 farms in England, abnormal gate was present in 11.8% of maiden gilts, 14.4% of pregnant gilts, and 16.9% of pregnant sows (KilBride et al., 2009).

Anil et al. (2009) reported that of all sows that were removed from a herd in the Midwestern United States, 10.2%, 15.0%, and 10.0% of parity 0, 1, and 2+, respectively, were removed for lameness. Furthermore, lame sows were 1.7 times more likely to be culled within 350 days of the lameness assessment than non-lame sows (Anil et al., 2009). However, the likelihood of culling for lameness decreases as sow age increases (Stalder and Serenius, 2004; Anil et al., 2005). In a study of 28 herds across the Midwestern United States and Canada, locomotion accounted for 13.2% of all culling events, and nearly 55% of sows culled for locomotion problems were culled before reaching parity 3 (Lucia Jr. et al., 2000). Locomotion was the cause of 14% of culls made at parity 0 and 18% of culls made at parity 1. The mean parity at removal for locomotion was 2.6, and the mean parity at removal for any reason was 3.3. The overall low parity at removal was mostly due to locomotion and reproductive problems, as females removed for these reasons had a shorter herd life and fewer parities than females removed for all other reasons ( $P < 0.01$ ; Lucia Jr. et al., 2000). Therefore, locomotion problems are a major contributor to reduced sow longevity.

Foot lesions are also a common issue in swine that leads to lameness and structural unsoundness (Ossent et al., 2010). Prevalence of at least one foot lesion is 80-98% in sows (Anil et al., 2007; Ossent et al., 2010; Sasaki et al., 2015), with the prevalence among lame sows at the top of the range (Ossent et al., 2010). The prevalence of lesions is higher in the lateral toes than the medial toes due to an increased proportion

of weight bearing and, therefore, increased stress on the lateral toes (Anil et al., 2007; Pluym et al., 2013b). Common foot lesions include vertical and horizontal wall cracks, elongated toes and dew claws, heel overgrowth and erosion, and cracks at the heel-sole junction and along the white line. These lesions can arise from several different causes, including inflammation, trauma, mechanical problems, and inferior horn quality (Ossent et al., 2010). While foot lesions certainly contribute to lameness, effects of foot lesions on longevity are less clear. Sows of younger parities were more likely to have white line cracks than sows of older parities ( $P < 0.05$ ; Anil et al., 2007), suggesting they may be contributing to early culling. However, older sows were more likely to have wall cracks and elongated toes and dew claws (Pluym et al., 2011).

Feet and leg conformation has been shown to affect longevity in sows. Tiranti and Morrison (2006) scored conformation of the front and rear legs on 203-day-old gilts ( $n = 961$ ) to assess retention rate through two parities. Conformation was scored on a scale of 1 to 9, with a score of 9 for the front limbs and 5 for the rear limbs being the ideal score. Lameness was the most common reason for removal, accounting for 22.1%. Downer sows or splayed legs caused 11.0% of removals, and 3.3% of removals were due to unsoundness/poor conformation. When a Wilcoxon test was used, conformation scores of both the front and rear legs had an effect ( $P < 0.02$ ) on sow removal for all reasons as well as removal for lameness. Inclusion of backfat thickness and farm as covariates in a Cox regression analysis, which analyzes survival time or time until an event occurs, revealed that sows with rear leg conformation scores  $\leq 4$  were 1.5 times more likely to be removed for any reason than sows with the ideal score of 5 ( $P = 0.03$ ). Sows with rear leg conformation scores  $\leq 4$  were also more likely than sows with ideal rear legs to be

removed for lameness ( $P = 0.01$ ). Sows with front leg conformation scores  $\leq 4$  tended ( $P = 0.06$ ) to have a higher removal risk for all reasons than sows with front leg conformation scores  $> 5$  (Tiranti and Morrison, 2006).

Serenius and Stalder (2007) also found that unfavorable leg soundness scores significantly ( $P < 0.001$ ) reduced length of productive life. At approximately 100 kg of body weight, Finnish crossbred gilts ( $n = 11,791$ ) were given a leg soundness score on a scale of 1 to 5, with 5 being the ideal score. Scores 1-2 and 4-5 were combined for analysis. Leg score significantly contributed to culling risk ( $P < 0.001$ ); productive life was markedly shortened in sows with a score of 1-2 compared to a score of 4-5, whereas sows with a score of 3 had only slightly shorter productive lives than sows with scores 4-5 (Serenius and Stalder, 2007).

Fernández de Sevilla et al. (2008) scored overall leg conformation and six specific morphological defects, excessive or abnormal hoof growth, splayed feet, plantigradism, straight pastern, sickle-hooked leg, and presence of bumps or injuries on the legs. All scores were on a scale of 0 to 2, with 2 being good conformation or absence of the morphological defect. Scores were taken at six months of age, at approximately 100 kg of body weight, and after first and second parturitions on purebred Duroc ( $n = 587$ ), Landrace ( $n = 239$ ), and Large White ( $n = 217$ ) sows with production records. Overall conformation score significantly ( $P < 0.01$ ) influenced sow survivability in all three breeds. The ideal score of 2 had the minimum hazard ratio, while the poorest score of 0 had the maximum hazard ratio. All specific morphological defects, except sickle-hooked legs, had a significant effect on survivability in at least one breed, but not all three. Excessive or abnormal hoof growth significantly ( $P < 0.01$ ) reduced survival in Duroc

and Landrace sows. Survival was significantly ( $P < 0.05$ ) reduced by straight pasterns and bumps and/or injuries on the legs in Duroc. Splayed feet reduced survival in Large White ( $P < 0.01$ ). Plantigradism reduced survival in Duroc and Large White ( $P < 0.05$ ) and tended ( $P < 0.1$ ) to reduce survival in Landrace (Fernández de Sevilla et al., 2008).

Low to moderate genetic correlations between conformation and longevity traits have been reported (López-Serrano et al., 2000; Serenius and Stalder, 2004; Nikkilä et al., 2013a; Sobczyńska et al., 2013; Aasmundstad et al., 2014b; Le et al., 2016), suggesting conformation traits could be used as indicator traits for sow longevity. Overall leg action was scored on a scale of 1 to 5, with 5 being the most ideal score, in purebred Landrace and Large White gilts when they weighed approximately 100 kg (Serenius and Stalder, 2004). Genetic and phenotypic correlations with length of productive life were directly estimated using a multi-trait model. A single-trait proportional hazard model was also used to describe length of productive life to account for censored records and model the distribution of longevity data more appropriately. The genetic correlation between estimated breeding values (EBV) of length of productive life from the single-trait proportional hazard model and overall leg action score from the multi-trait model was also estimated. Phenotypic correlations between length of productive life and overall leg action were low (0.04) in both Large White and Landrace. While still low in Large White, genetic correlations were moderate in Landrace when estimated with the multi-trait model ( $0.32 \pm 0.17$  and  $0.17 \pm 0.16$ , in Landrace and Large White, respectively). Genetic correlations were even lower when using the single-trait proportional hazard model for length of productive life (0.14 and 0.04 in Landrace and Large White, respectively; Serenius and Stalder, 2004).

Sobczyńska et al. (2013) estimated genetic and phenotypic correlations between three longevity traits and exterior index score, which was scored on a scale of 0 to 100 and included overall type, leg status, number and quality of teats, muscle, and length using 19,423 Polish Landrace sows from 161 herds. The longevity traits were length of life, defined as the number of days between birth and culling, length of productive life, defined as the number of days between first and last farrowing, and number of litters produced by the sow in her lifetime. Genetic and phenotypic correlations were estimated using an animal model and the restricted maximum likelihood (REML) method. While both genetic and phenotypic correlations between the different definitions of longevity were very high (0.99-1.00 and 0.94-0.99, respectively), genetic and phenotypic correlations between longevity and exterior index score were low and not significantly different from zero (-0.22 to 0.08 and -0.004 to 0.006, respectively; Sobczyńska et al., 2013). The exterior index score was a very broad composite trait that took many aspects of conformation into account. More specific assessments of conformation traits would likely have resulted in greater and more consistent correlations. Additionally, the authors also acknowledge that most pigs were given scores of 75 or 90 rather than using the full range of 0 to 100, and the scoring was done by different observers. They also believe a linear model was not the best fit for the exterior index score trait (Sobczyńska et al., 2013), providing further evidence that a different approach is needed to assess correlations between longevity and conformation.

López-Serrano et al. (2000) estimated genetic correlations between stayability traits and exterior traits in Large White ( $n = 8879$ ) and Landrace sows ( $n = 4881$ ). The sows used in this study were selected on performance traits and exterior condition around

105 kg of bodyweight. Stayability from first to second litter (STAY12) and from first to third litter (STAY123) were assessed. Sows were only included in the study if they produced at least one litter. Exterior traits of leg status, sow length, muscle, sow height, and overall type were evaluated on a scale of 1 to 9, with 9 being the ideal score. Genetic correlations were estimated using Bayesian multi-trait models with Gibbs sampling. Moderate favorable genetic correlations were found between leg score and both stayability traits in Landrace ( $r = 0.19$  and  $0.36$  for STAY12 and STAY123, respectively). However, genetic correlations between leg score and stayability were much lower and near zero in Large White ( $r = 0.08$  and  $0.002$  for STAY12 and STAY123, respectively). The remaining exterior traits, length, muscle, height, and type, exhibited low and inconsistent genetic correlations with stayability that were near zero in both breeds, ranging from  $-0.07$  (type and STAY12 and muscle and STAY123) to  $0.04$  (height and STAY12) in Large White and  $-0.12$  (type and STAY12) to  $0.07$  (length and STAY123) in Landrace. Low and inconsistent genetic correlations could be partially due to the fact that exterior traits were scored subjectively by multiple evaluators (López-Serrano et al., 2000). Genetic correlations may have also been higher if sows in this study had not been pre-selected for exterior traits and did not have to complete one parity to be included, as these practices likely decreased variation in the study population.

Le et al. (2016) assessed correlations between longevity traits - stayability until parity 2 and lifetime number of litters produced, and conformation traits - movement and overall score, in purebred Yorkshire nucleus and multiplier sows. Movement and overall score were scored based on the way the gilt moved and the general appearance of the legs, respectively, on a scale of 1 to 3, with 1 being poor and 3 being excellent.

Conformation scoring occurred when the gilts were approximately five months of age and 100 kg. Both a conventional linear model (REML) and a Bayesian threshold model (Gibbs sampler) capable of modeling more appropriate non-normal distributions for the conformation traits and stayability until parity 2 were utilized. Phenotypic correlations were low (0.02-0.04) between the conformation traits and longevity traits when the linear model was used. However, with the Bayesian threshold model, phenotypic correlations were much higher at 0.47 to 0.49 for movement and 0.31 to 0.32 for overall score and the longevity traits. On the contrary, genetic correlations were higher when the linear model was used compared to the Bayesian threshold model, though this difference was not large. Genetic correlations between movement and the longevity traits were 0.39 to 0.42 and 0.36 when linear and Bayesian methods were used, respectively. Genetic correlations between overall score and longevity traits were slightly lower at 0.20 to 0.24 and 0.17 to 0.18 when linear and Bayesian methods were used, respectively. All genetic correlations between conformation and longevity traits favored excellent conformation and were significantly different from zero (Le et al., 2016). Longevity traits were only measured for sows that produced at least one parity. Correlations may have been stronger if gilts that failed to produce a litter were included in the study.

Aasmundstad et al. (2014b) assessed correlations between stayability until parity 2 and lifetime number of litters produced (defined similar to Le et al., 2016) and four conformation traits: motorics, locomotion scored on a scale of 4 to 7; front leg score, appearance of knees and pasterns scored on a scale of 1 to 7; hind leg score, considering stance, hocks, and pasterns scored on a scale of 1 to 7; and hind leg standing under, alignment of hips and hooves scored on a scale of 4 to 7. A score of 4 was considered

optimal for all conformation traits. Conformation traits were scored in purebred nucleus and multiplier Landrace gilts between 100 and 200 days of age. Two multivariate models using REML algorithms were used for analysis; model 2 included EBV at removal to account for early culling due to genetic selection, whereas model 1 did not. Phenotypic correlations between all longevity and conformation traits were near zero (range -0.02 to 0.01). Genetic correlations are summarized in table 1.1. No genetic correlations between longevity and conformation traits were significantly different from zero except front leg score and stayability until parity 2 when model 2 including the EBV correction was used (Aasmundstad et al., 2014b). Front and hind leg scores had optimal intermediate values, and the models employed were linear. Therefore, it might be expected that accounting for intermediate values could increase correlations. However, the authors initially fit a 2<sup>nd</sup> degree polynomial regression to account for a non-linear genetic effect, but it was removed from the final model due to being non-significant (Aasmundstad et al., 2014b).

Table 1.1. Genetic correlations between longevity<sup>1</sup> and conformation<sup>2</sup> traits adapted from Aasmundstad et al. (2014b).

	<b>MOT</b>	<b>FLEG</b>	<b>HLEG</b>	<b>HSTU</b>
<b>STAY 1</b>	0.00 ± 0.08	-0.13 ± 0.07	0.08 ± 0.08	0.02 ± 0.09
<b>LNL 1</b>	0.02 ± 0.07	-0.06 ± 0.06	0.10 ± 0.07	-0.02 ± 0.07
<b>STAY 2</b>	-0.05 ± 0.07	-0.12 ± 0.06	-0.00 ± 0.08	-0.10 ± 0.08
<b>LNL 2</b>	-0.03 ± 0.07	-0.06 ± 0.05	0.03 ± 0.07	-0.11 ± 0.07

<sup>1</sup>STAY1 = stayability until parity 2 model 1 (excluding EBV correction), LNL1 = lifetime number of litters produced model 1 (excluding EBV correction), STAY2 = stayability until parity 2 model 2 (including EBV correction), LNL2 = lifetime number of litters produced model 2 (including EBV correction)

<sup>2</sup>MOT = motorics, FLEG = front leg score, HLEG = hind leg score, HSTU = hind leg standing under

Correlations between two longevity and 17 conformation traits were evaluated in Nikkilä et al. (2013a). The longevity traits were length of productive life [defined



similarly to Serenius and Stalder (2004)] and lifetime number of litters [defined similarly to Le et al. (2016) and Aasmundstad et al. (2014b)]. The conformation traits subjectively evaluated were six body structure traits: body length, body depth, body width, rib shape, top line, and hip structure; five front leg structure traits: legs turned, buck knees, pastern posture, foot size, and uneven toes; five rear leg structure traits: legs turned, leg posture, pastern posture, foot size, and uneven toes; and overall leg action. Each trait was scored on a 9-point scale. Legs turned in/out on both feet were transformed into deviations from the optimal intermediate score for analysis. Conformation traits were scored on grandparent ( $n = 461$ ) and parent ( $n = 986$ ) maternal line gilts averaging 190 days of age and 124 kg of body weight. Genetic correlations were estimated using both multivariate linear animal models with the REML algorithm and Markov Chain Monte Carlo methods with Gibbs sampling to account for censoring of records. Genetic correlations between longevity and conformation traits are summarized in table 1.2. Genetic correlation estimates were similar between methods of estimation and between the two longevity traits. Short body length (close to intermediate in this dataset), wide body width, and round rib shape were favorable for longer productive life and a greater lifetime number of litters. Hip structure and length of productive life had a genetic correlation approaching significance ( $P < 0.10$ ); level (as opposed to steep) hip structure was favorable for increased length of productive life. Most front and rear leg conformation traits were lowly and insignificantly ( $P > 0.05$ ) correlated with longevity traits except rear foot size ( $P < 0.05$ ). Larger feet were preferred for increased longevity; however, the distribution of foot scores in this data set suggest intermediate foot size is superior. Front legs turned in/out was moderately and suggestively ( $P < 0.10$ ) correlated with both longevity traits.

However, legs that were turned were favorable, contrary to expectations and previous research. Genetic correlations between overall leg action and longevity traits were low and insignificant ( $P > 0.05$ ), though the correlation was in the direction favoring poor conformation for improved longevity (Nikkilä et al., 2013a).

Table 1.2. Genetic correlations between longevity<sup>1</sup> and conformation<sup>2</sup> traits adapted from Nikkilä et al. (2013a).

		LPL		LNL	
		LM <sup>3</sup>	MCMC <sup>4</sup>	LM <sup>3</sup>	MCMC <sup>4</sup>
<b>Body structure</b>	BL	-0.69***	-0.64	-0.64**	-0.61
	BD	-0.28	-0.23	-0.28	-0.22
	BWD	0.53*	0.52	0.44*	0.44
	BRS	-0.72***	-0.68	-0.69***	-0.67
	BTL	-0.25	-0.25	-0.18	-0.20
	BHS	-0.42	-0.40	-0.35	-0.35
<b>Front leg structure</b>	FLTD	0.48	0.46	0.49	0.44
	FBK	0.13	0.11	0.12	0.09
	FPP	-0.06	-0.11	-0.05	-0.09
	FFS	-0.04	0.05	0.02	0.14
	FUT	-0.00	0.02	0.05	0.07
<b>Rear leg structure</b>	RLTD	-0.30	-0.29	-0.29	-0.28
	RLP	-0.30	-0.22	-0.35	-0.25
	RPP	0.11	0.13	0.07	0.10
	RFS	0.51*	0.54	0.51*	0.58
	RUT	-0.13	-0.16	-0.07	-0.15
	OLA	0.11	0.15	0.15	0.19

<sup>1</sup>LPL = length of productive life, LNL = lifetime number of litters

<sup>2</sup>BL = body length, BD = body depth, BWD = body width, BRS = body rib shape, BTL = body top line, BHS = body hip structure, FLT = front legs turned, FBK = front buck knees, FPP = front pastern posture, FFS = front foot size, FUT = front uneven toes, RLT = rear legs turned, RLP = rear leg posture, RPP = rear pastern posture, RFS = rear foot size, RUT = rear uneven toes, OLA = overall leg action

<sup>3</sup>Linear multivariate animal model genetic correlation estimate differs from 0 by \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$

<sup>4</sup>Markov Chain Monte Carlo method

Results of studies assessing links between conformation and longevity can vary widely. Comparisons across studies can be difficult due to different trait definitions, methods of trait measurement (particularly scale used for conformation trait scoring), and methods of analysis used between studies. Differences in results also occur due to the subjectivity of scoring conformation traits, variable numbers of animals and statistical power, and differences in population structures including breed, the average and variance of the trait being considered within the population, and the selection strategy implemented in the population. This underscores the importance of developing standardized and reliable methods for assessing conformation traits. Further study will be needed to identify repeatable links between conformation and longevity traits both genetically for genetic improvement programs at the nucleus level and phenotypically for selection of replacement females to go to the commercial level. Given a favorable relationship between conformation and longevity, conformation traits may be valuable indicator traits to select for improved longevity at all stages of the breeding pyramid, particularly as it can be measured earlier in life.

## **1.2 Relationship Between Conformation Traits and Sow Productivity**

In addition to decreased longevity, poor conformation may also contribute to lower sow productivity. However, this is not readily apparent from studies assessing reasons for sow removal. Anil et al. (2005) found that sows had higher odds of being culled for lameness as lifetime mean number of litters farrowed per year and number born alive increased. Since only a single reason for culling was designated, this is likely due to more productive sows being less likely to be culled due to productive or reproductive reasons, and therefore, more likely to be culled due to lameness. In a study by Engblom

et al. (2007), sows culled for old age had higher numbers of piglets born alive and weaned (12.2 and 10.2, respectively) per litter than sows culled for lameness and/or foot lesions (11.3 and 9.8, respectively); however, sows culled for old age were culled at parity 7.9 on average, whereas lame sows were culled at an average parity of 3.4 (Engblom et al., 2007). In both Anil et al. (2005) and Engblom et al. (2007), a single reason for culling was documented for each sow. It is probable that sows culled for other reasons, particularly for reproductive disorders or low productivity, may have also been lame. Fabà et al. (2018) found that gilts identified as lame during gestation lost more backfat during lactation (-1.8 mm;  $P = 0.001$ ), had a longer wean-to-estrus interval (+3.4 days;  $P = 0.031$ ), and tended to have more stillborn piglets (+0.7 piglets;  $P = 0.089$ ) than gilts that were never categorized as lame. Gilts that were classified as lame during rearing weaned fewer piglets than those that were never lame (+1.2 piglets;  $P = 0.016$ ). Additionally, 14% of gilts that were culled during first parity gestation were identified as lame at some point during gestation but were given a different reason for removal (Fabà et al., 2018).

Fernández de Sevilla et al. (2009a) scored overall leg condition on a scale of 0 to 2 in a Duroc nucleus and a Duroc nucleus/multiplier herd and recorded the presence or absence of six structural abnormalities—excessive hoof growth, splayed feet, plantigradism, straight pastern, sickle-hooked leg, and bumps or injuries on the legs—to assess their influence on death during productive life and voluntary culling for low productivity or low fertility. Leg condition score had no effect on death during productive life, nor did any of the conformation abnormalities. However, leg condition did have a significant effect on culling for low productivity and low fertility ( $P < 0.001$ ); sows with

poor leg condition were more likely to be culled for both reasons than sows with good leg condition. Presence of excessive hoof growth and bumps or injuries on the legs also increased the likelihood of culling for both low productivity and low fertility ( $P < 0.01$ ). Plantigradism increased low productivity culling risk ( $P < 0.05$ ), and sickle-hooked leg increased low fertility culling risk ( $P < 0.05$ ; Fernández de Sevilla et al., 2009a).

Fitzgerald et al. (2012) assessed the effects of excessive hoof growth, length differences between the medial and lateral toe of the hoof, and cracks in the outer hoof wall on sow productivity measures, including number of piglets born alive, pre-weaning mortality, piglets weaned per litter, litter weaning weight adjusted for cross-fostering practices, and lactation feed intake. Each foot defect was scored on a scale of 0 to 3, with 0 being the ideal score. Number of piglets born alive was not affected by any foot disorder ( $P > 0.75$ ). Pre-weaning mortality was higher in sows with more severe toe length differences and hoof cracks ( $P = 0.02$ ). Sows with toe length differences also weaned fewer piglets ( $P = 0.02$ ), while sows with hoof cracks showed the same trend ( $P = 0.10$ ). While pre-weaning mortality and number of piglets weaned were not significantly impacted by excessive hoof growth, sows with excessive hoof growth had decreased litter weaning weights ( $P = 0.03$ ). Sows with hoof cracks also tended to have decreased litter weaning weights ( $P = 0.07$ ). While sows with excessive hoof growth spent less time standing and eating than sows without foot disorders ( $P = 0.01$ ), differences in amount of feed consumed did not reach significance ( $P = 0.13$ ; Fitzgerald et al., 2012).

Direct effects of foot lesions on sow productivity were observed in several studies. Pluym et al. (2013b) found that white line cracks were associated with increased number of stillborn piglets (SB;  $P = 0.036$ ), heel overgrowth and erosion was associated

with more crushed piglets ( $P = 0.017$ ), and wall cracks increased the likelihood of mummified fetuses ( $P = 0.044$ ). Lisgara et al. (2015) identified associations between lesions on the heel ( $P \leq 0.001$ ) and sole ( $P = 0.019$ ) of front feet and number of piglets born alive (NBA). Number of piglets weaned (NW) was influenced by heel ( $P = 0.003$ ) and sole ( $P \leq 0.008$ ) lesions on any foot and white line and wall lesions ( $P = 0.008$ ) on rear feet. Heel lesions ( $P = 0.02$ ) on any foot and sole lesions ( $P = 0.02$ ) and dew claw length ( $P = 0.009$ ) on front feet were associated with wean-to-estrus interval (WEI; Lisgara et al., 2015). Sasaki et al. (2015) found a tendency for decreased farrowing rate in sows with at least one foot lesion score  $\geq 2$  on a scale of 0 to 4 ( $P < 0.1$ ). However, no effects of foot lesion scores  $\geq 2$  on other productivity traits were identified (Sasaki et al., 2015). Enokida et al. (2011) did not identify any associations between total foot lesion score (sum of individual foot lesion scores) or highest foot lesion score and productivity traits. Taken together, these results suggest that individual foot lesions contribute to decreases in productivity in different ways and should be considered separately.

Additional studies have focused on the genetic relationship between conformation traits and productivity traits. Serenius et al. (2004) assessed genetic associations between productivity traits: total number born (TNB), SB, pre-weaning mortality (PWM), age at first farrowing (AFF), and first farrowing interval (FFI), and two conformation traits (overall leg action and buck-kneed forelegs) in purebred Large White and Landrace. While a few correlations were moderate to high, their standard errors were high as well. In addition, the genetic correlations differed considerably between the two breeds. Therefore, the authors concluded that no clear associations were present. In Landrace, the genetic correlation between overall leg action and lifetime TNB was larger than the

standard error ( $0.28 \pm 0.14$ ) and in the same direction as in Large White (Serenius and Stalder, 2004), suggesting that selection for ideal overall leg action may result in genetic improvement for lifetime piglet production and vice versa. While phenotypic correlations were nearly zero, Knauer et al. (2011) found moderate genetic correlations between TNB and subjective scores of rib width, front leg side view, rear leg side view, rear legs rear view, and locomotion (0.54, -0.47, -0.29, 0.84, and -0.51, respectively). Wide rib width was associated with greater TNB. The genetic correlation between locomotion and TNB was favorable. The genetic correlations between TNB and front leg side view, rear leg side view, and rear legs rear view were also considered favorable, though these traits have intermediate optimums and the score distributions were centered around the intermediate value (Knauer et al., 2011). Aasmundstad et al. (2014b) assessed phenotypic and genetic correlations between the sum of TNB and litter weaning weight in parities 1 and 2 and locomotion, hind leg, front leg, and hind leg standing under scores. Phenotypic correlations were nearly zero in this study as well. Genetic correlations were also low, though the correlations between parity 1 and 2 TNB and front leg and hind leg standing under scores were low to moderate ( $0.22 \pm 0.07$  and  $-0.20 \pm 0.10$ , respectively). Front leg score has an intermediate optimum, though the correlation with hind leg standing under is more definitively favorable, as a lower score is ideal (Aasmundstad et al., 2014b). Le et al. (2015) also estimated genetic correlations between several productivity and conformation traits. Productivity traits included in the analysis were TNB, NBA, SB, and WEI in parities 1 and 2. Conformation traits included in the analysis were movement and overall leg score on a scale of 1 to 3, with 3 being favorable. New methods of scoring these traits were introduced while the study (Le et al., 2015) was underway. A new

movement score was on a scale of 1 to 7 with an intermediate optimum, and a new overall score was on a scale of 1 to 6, with 1 being the ideal score. Additionally, new traits of toes quality, front leg quality, rear leg quality, and standing under position were introduced and subsequently used in the study. Each of these traits has an optimum value of 4 and a maximum value of 7, but the scale of front and rear leg quality begins at 1, while the scale of toes quality and standing under position begins at 4. Genetic correlations were moderate and significantly different from zero between the old movement score and TNB and NBA in both parities 1 and 2 ( $0.20 - 0.36$ ) and WEI in parity 2 ( $-0.35 \pm 0.11$ ). These correlations were favorable as improved old movement score was associated with increased TNB and NBA and decreased WEI. However, with the new scoring system, no correlations between movement score and any productivity trait differed from zero. This could be due, at least in part, to fewer sows being scored with the new system. Even so, a few moderate genetic correlations existed between new conformation traits and productivity traits. Toe quality and new overall score were favorably correlated with NBA in parity 1 ( $-0.35 \pm 0.13$ , and  $-0.31 \pm 0.13$ , respectively). Front leg quality was correlated with SB in parity 1 ( $0.26 \pm 0.10$ ); while front leg quality had an intermediate optimum, this genetic correlation suggests that sows with cow-legged stance, straight knees, and turned out and post-legged pasterns, were more likely to have stillborn piglets in parity 1. Finally, standing-under position was favorably correlated with TNB and NBA in parity 1 ( $-0.39 \pm 0.16$  and  $-0.35 \pm 0.18$ , respectively) and parity 2 ( $-0.54 \pm 0.18$  and  $-0.53 \pm 0.18$ , respectively; Le et al., 2015).

Genetic aspects of foot lesions have not been well documented in swine.

However, genetic correlations were identified between foot lesions and production traits



in dairy cattle. Most of these correlations were favorable, except correlations between protein yield and heel horn erosion, sole hemorrhage, and sole ulcer lesions (0.24, 0.11, and 0.2, respectively; Buch et al., 2011). Favorable genetic correlations were found between digital dermatitis and milk production, fat production, non-return to estrus after 56 days, and lifespan (-0.31, -0.43, 0.48, and -0.16, respectively; Onyiro et al., 2008). Favorable genetic correlations also existed between number of inseminations and dermatitis and heel-horn erosion (0.32 and 0.22, respectively) and between days from calving to first insemination and sole ulcer (0.33; Buch et al., 2011). Lameness was also favorably correlated with both infectious and noninfectious foot lesions analyzed as composite traits including several lesion types. Genetic correlations between lameness and infectious lesions were 0.51 when pedigree data was used and 0.44 when genomic data was used. Genetic correlations between lameness and non-infectious lesions were 0.91 and 0.74 using pedigree and genomic data, respectively (Dhakal et al., 2015).

As with longevity traits, conformation traits could serve as valuable indicator traits for economically important production traits. Many approaches have been taken to assess conformation traits and their relationship to production traits. A standardized and reliable method of phenotyping conformation traits is necessary to accurately determine the relationships that can be used in selection programs and breeding schemes. The studies presented show that genetic correlations may exist between conformation traits and economically important production traits. Given appropriate phenotyping methods and accurate and favorable genetic correlations, conformation traits would serve as valuable indicator traits for production traits as they can be measured earlier in life.

### **1.3 Economic Importance of Conformation**

Conformation traits are of high economic importance to the swine industry. However, few exact economic value estimates exist. Willgert (2011) estimated cost associated with lameness in English sow herds. Assuming treatment for lameness consists of isolating the sow with deep bedding, medication, and a bandage, which requires 45 minutes of additional attention from a farm employee and five minutes of time from a veterinarian, the cost to treat a lame sow is £19. With an exchange rate of £1 to \$1.41 (May 19, 2021), this is equal to \$26.79. Lameness can also decrease productivity through reduced piglet production. Using values for reduced number of pigs per sow per year caused by early removal of lame sows (Anil et al. 2005) and increased piglet mortality in lame sows (Grandjot, 2007), Willgert (2011) estimated the cost of reduced production due to lameness to be £84, or \$118.44 per lame sow. The cost of replacing a sow due to lameness was estimated at £39 (\$54.99) if the sow was able to be sold, and £162.5 (\$229.13) if she had to be euthanized (Willgert, 2011). If a sow only required one treatment for lameness and recovered quickly without any effects on production, the cost of lameness may only be £19 (\$26.79); however, if a sow is treated for lameness, has reduced production, and must be euthanized, the total cost could be at least £265.5, or \$374.36 (Willgert, 2011).

Jensen et al. (2012) estimated economic impacts of nine leg disorders in finisher (90-100 kg) pigs. The nine leg disorders are: four causes of infectious arthritis, *Mycoplasma hyosynoviae*, *Erysipelothrix rhusiopathiae*, *Haemophilus parasuis*, and *Streptococcus suis*; three physical injuries, bone fractures of the leg(s), lesions to the claw wall (white line and wall lesions), and lesions to the volar area of the feet (sole, toe, and heel lesions); and two types of osteochondrosis, osteochondrosis manifesta (thickened

and uneven cartilage) and osteochondrosis dissecans (lesions of fissured articular cartilage). Ten Danish veterinarians answered a questionnaire on the production consequences associated with each leg disorder, including likelihood of euthanasia and treatment with antibiotics and/or analgesics and changes in average daily gain (ADG) and feed conversion ratio (FCR). Responses were used to form probability distributions, with the median as the most likely value and the maximum and minimum responses as the maximum and minimum values. For each leg disorder, 10,000 consequences were sampled from the probability distribution. The simulated consequences were used to calculate the impact of each leg disorder on the profit margin in the interval from 30 kg until slaughter. The profit margin (revenue minus variable costs) of a market hog without any leg disorders was estimated at 104 Danish DKK. With an exchange rate of 1 DKK to 0.16 US dollars (May 19, 2021), this is equal to \$16.64 US. Bone fractures resulted in lowest profit margin at -410 DKK (-\$65.6), followed by *Erysipelothrix rhusiopathiae* at -186 DKK (-\$29.76). Lesions to the volar area of the feet and *Mycoplasma hyosynoviae* were the only two leg disorders that still maintained a positive, but lower, profit margin at 5 DKK (\$0.80) and 18 DKK (\$2.88), respectively. The remaining two infectious arthritis causes resulted in profit margins of -86.5 DKK (-\$13.84), and lesions to the claw wall reduced profit margin to -27 DKK (-\$4.32). Profit margins were -155 DKK (-\$24.8) and -110 DKK (-\$17.6) for osteochondrosis manifesta and osteochondrosis dissecans, respectively (Jensen et al., 2012).

Poor conformation and lameness have a negative impact on farm profitability through decreased sow longevity. While few direct estimates of economic losses due to lameness-caused early culling were found, economic evaluations of sow longevity have

been conducted. Faust et al. (1993) used simulations to compare profitability of an integrated production system with nucleus, multiplier, and commercial levels when sows were culled after one, five, or ten parities. Systems with the lowest sow replacement rates at the commercial level were the most profitable. Replacing sows after one parity in the nucleus was the most profitable strategy due to increased genetic progress. Replacement rates at the multiplier did not have as great of an effect on profitability. The top overall systems for returns per pig and total returns over expenses replaced sows after one parity in the nucleus and ten parities at the commercial level, with less sensitivity to multiplier replacement rate. Faust et al. (1993) also reported that commercial systems that did not cull sows until parity ten could justify paying more for replacement gilts; thus, they were able to purchase gilts with higher genetic quality to further increase farm profitability. Specifically, ten parity commercial units were able to pay \$113 more per gilt than comparable five parity commercial systems, at 450% market value, whereas one parity commercial herds could only afford to pay 175% of market value for replacement gilts (Faust et al., 1993). Furthermore, Stalder et al. (2003) demonstrated that a replacement gilt must remain in the herd for three parities to reach a positive net present value, or become profitable after covering her purchase, development, and maintenance costs. While changes in market values, production costs, inflation, etc. can change the number of parities required to reach a positive net present value (Rodriguez-Zas et al., 2003; Stalder et al., 2003), commercial sows with longer herd lives will be more profitable than sows with shorter herd lives, provided the economic context is not highly unfavorable for production (Rodriguez-Zas et al., 2003).

Economic assessments of conformation traits in the literature are limited. Treatment cost of lameness (Willgert, 2011; Jensen, 2012) that may arise from poor conformation gives conformation traits economic value themselves. However, the most straight-forward means of including conformation traits in a breeding program is as indicator traits for longevity and production traits. In this scenario, economic values would be estimated for longevity and production traits in the breeding objective and related to conformation traits through their genetic correlation. Improving longevity has been shown to be profitable (Faust et al., 1993; Rodriguez-Zas et al., 2003; Stalder et al., 2003), and including genetically correlated conformation traits in a selection index would help drive genetic progress.

#### **1.4 Management Factors Influencing Conformation and Lameness**

Many management factors have been examined for effects on conformation and lameness. Cador et al. (2014) assessed differences in pen structures and other risk factors for lameness among sows housed in pens in conventional farming systems. This study included 108 herds located in western France. Herd management and husbandry practices, sow and premise observations and measurements, and climatic conditions were obtained via farm staff surveys and researcher observation and measurement. For climatic conditions, ammonia was quantitatively measured, while floor design/condition, humidity, and cleanliness were evaluated on a 2-point subjective scale of good/poor, low/high, and clean/dirty, respectively. The four pen structures assessed were small groups with walk-in lock-in stalls, small groups with partial feeding stalls, large dynamic groups with electronic sow feeders (ESF), and large static groups with ESF. Claw lesions were scored on the hind legs using a scale of 0 to 3 and summed over both hind feet.

Lameness was scored on a 5-point system but converted to a 2-point system to focus on severe lameness only. A subset of sows on each farm was randomly selected to be evaluated for several types of claw lesions and gait. Principal component analysis was used to combine the claw lesion and lameness scores into a single variable called leg disorders. This leg disorders variable ultimately included frequency of lameness, mean score for heel lesions, heel-sole junction lesions, wall lesions, mean score for major claw growth, and dewclaw growth and integrity. Farms were split into two groups using hierarchical cluster analysis. Group 1 (n = 40 farms) was considered to have mild leg disorders, while group 2 (n = 68 farms) was considered to have major leg disorders. Farms in group 2 had scores for lameness, dew claw growth and integrity, heel lesions, and wall lesions that were higher than average. However, farms in group 1 had higher claw growth and heel-sole junction lesions than average. Small groups with walk-in lock-in stalls provided the lowest risk of leg disorders and was least likely to be associated with group 2 (major leg disorders). The relative risk (RR) of the other pen structures were 1.4 for small groups with partial feeding stalls, 1.7 for large dynamic groups with ESF, and 2.0 for large static groups with ESF. Providing bedding reduced the risk of leg disorders; the relative risk of a concrete slatted floor was 9.9. Other factors that increased the probability of being in group 2 with major leg disorders were dirty floors (RR = 1.6, P = 0.03), high (> 100) number of sows per stockman (RR = 1.5, P = 0.03), high (> 10 ppm) levels of ammonia (RR = 1.5, P = 0.01), and low (< 3.1 kg/d) amount of feed provided to gilts at the end of gestation (RR = 1.5, P = 0.04; Cador et al., 2014).

Willgert et al. (2014) also evaluated risk factors for lameness on 76 sow farms in England. These farms included both indoor and outdoor systems; risk factors were

determined for both types of production systems considered together and for just indoor systems considered separately. One pen was randomly selected at each farm; a maximum of 20 sows were randomly selected within that pen for lameness assessment, scored as a binary trait. When both indoor and outdoor systems were considered, based on univariate analysis, the number of animals/pen ( $P < 0.0001$ ), floor type ( $P = 0.04$ ), piglets born alive/sow/year ( $P = 0.02$ ), and number of sows in care of stockman ( $P = 0.01$ ) were identified as risk factors for lameness. When only indoor systems were considered, significant risk factors were area of pen ( $P = 0.02$ ), stocking density ( $P = 0.01$ ), floor type ( $P = 0.03$ ), and sows with less than two litters ( $P = 0.04$ ). Based on multivariate analysis combining both indoor and outdoor systems, farms with a medium number of piglets born alive/sow/year (19.5 to 25.5) had the greatest risk of lameness [RR = 2.0 compared to farms with less than 19.5 piglets born alive/sow/year ( $P = 0.02$ ) and RR = 0.5 for farms with greater than 25 piglets born alive per sow per year compared to medium ( $P = 0.01$ )]. There was a lower risk of lameness when a stockman cared for a low (actual number not defined) number of sows compared to medium or high numbers of sows (RR = 0.4,  $P = 0.03$ ). When only indoor systems were considered, large (actual number not defined) pen size increased the risk of lameness compared to small and medium pen size (RR = 12.1;  $P = 0.02$ ). Sows in parities 3 to 6 had a decreased risk of lameness compared to sows in parity 2 and below (RR = 0.3;  $P = 0.01$ ; Willgert et al., 2014).

Risk factors for development of lameness on 15 sow herds in Belgium were also assessed (Pluym et al., 2017). All herds included in this study used group housing of gestating sows on concrete without bedding and a batch production system. Farms were visited and data collected just before and three to five days after moving sows from

insemination stalls to group gestation pens four weeks after insemination. Lameness was considered a binary trait, either not lame or became lame between visit 1 and visit 2.

Variables assessed for their role in the development of lameness included parity, breed, origin of replacement gilts, herd size, backfat thickness, feeding strategy during rearing (i.e., *ad libitum* or restricted), skin lesions, sow dirtiness, type of group housing system (i.e., free access stalls, ESF, trough feeding), group size, total area/sow, solid area/sow, flooring quality, floor slipperiness, floor wetness in the lying area and walking area, floor dirtiness, cleaning protocol of the gestation unit, and water supply (*ad lib* or restricted). Each variable was assessed for effect on lameness with univariate models, and a final multivariate model was built with all variables significant ( $P < 0.05$ ) and not highly correlated to other variables (Spearman's rank correlations  $< 0.6$ ). Sow dirtiness, herd size, and total floor area/sow made it into the final multivariate model. An increase in floor area per sow from 1.7 m<sup>2</sup> to 3.0 m<sup>2</sup> reduced the odds of developing lameness (OR = 0.40,  $P = 0.031$ ). Dirty sows with  $> 10\%$  of the body covered with feces had greater odds for development of lameness compared to clean sows (OR = 2.33,  $P < 0.001$ ). This association may be due to lame sows spending more time lying down than non-lame sows, particularly if they lay down in the dunging area to avoid competition for space in the lying area. The correlation was high between floor dirtiness and sow dirtiness ( $\rho = 0.612$ ,  $P < 0.05$ ); however, floor dirtiness was not associated with development of lameness in the univariate model ( $P = 0.482$ ), and probably did not cause the higher odds for lameness via sow dirtiness. The odds of developing lameness were decreased with increasing herd size from 144 to 750 sows (OR = 0.71,  $P = 0.02$ ). Herd size was significantly correlated with group size ( $\rho = -0.38$ ,  $P < 0.001$ ) and origin of replacement



gilts ( $p = -0.58$ ,  $P < 0.001$ ). Both group size and origin of replacement gilts were significant in univariate models ( $P = 0.006$  and  $P = 0.01$ , respectively) despite not making it into the final multivariate model. Larger herds tended to have smaller group sizes and reared replacement gilts rather than purchasing them, both of which resulted in lower odds of developing lameness based on the fit of univariate models. Parity was significant ( $P = 0.043$ ) in the univariate model and backfat thickness and skin lesions were approaching significance ( $P = 0.058$  and  $P = 0.073$ , respectively), but did not remain in the final multivariate model (Pluym et al., 2017).

Body condition score (BCS) was associated with foot lesions in a study of sows at Midwestern harvest facilities, with higher BCS being favorable (Knauer et al., 2007). Specifically, sows with a BCS of 1 had a higher probability of heel lesions on both the front ( $P = 0.04$ ) and rear ( $P = 0.01$ ) feet than sows with a BCS of 2 to 4. Sows with a BCS of 4 were less likely to have cracked hooves on the rear feet than sows with a BCS of 1 to 3 ( $P = 0.01$ ). On the front feet, cracked hooves were least likely in sows with a BCS of 4 and most likely in sows with a BCS of 1 to 2 ( $P = 0.01$ ). The probability of digital overgrowth was highest in sows with a BCS of 1 to 2 and lowest in sows with a BCS of 4 in the front feet ( $P = 0.01$ ), and lower in sows with a BCS of 4 than sows with a BCS of 1 to 3 in the rear feet ( $P = 0.01$ ; Knauer et al., 2007). However, Anil et al. (2007) found that increased body weight on day 109 of gestation increased the odds of wall lesions ( $P < 0.05$ ). Higher back fat on day 109 of gestation resulted in increased likelihood of heel lesions ( $P < 0.05$ ) but decreased likelihood of overgrown heels ( $P < 0.05$ ). Calderón Díaz et al. (2013) found that sows with a BCS of 2 had a lower risk of having white line cracks

and wall crack scores greater than the median score mid-way through parity 2 gestation than sows with a BCS of 3.

#### **1.4.1 Comparison of Production Systems**

Prevalence of lameness was compared between sows kept in organic ( $n = 9$  farms) and conventional ( $n = 44$  farms) production systems in Denmark (Knage-Rasmussen et al., 2014). In the organic production system, sows were group fed, had access to outdoor pasture year-round during gestation and insemination, farrowed in huts on individual pasture pens, and lactated for at least seven weeks. In the conventional system, sows were housed in group pens ( $n = 36$  farms) or individual stalls ( $n = 8$  farms) during gestation, individually fed via feeding stalls or electronic sow feeders, farrowed in indoor crates, and weaned after four weeks of lactation. A lower prevalence of lameness was observed in gestating sows in organic (5.4%) compared to conventional (24.3%) systems. The authors hypothesized this was likely due to pasture providing a softer surface to stand and walk on than concrete. It may be worth noting that the organic herds were visited twice whereas conventional herds were only visited once, and the first round of organic herd visits did not begin until after all conventional herd visits had been completed. Elongated and/or uneven toes (scored jointly as a binary trait) did not affect lameness among organic sows ( $P > 0.05$ ); this was not assessed in conventional herds (Knage-Rasmussen et al., 2014). In Croatia, indoor ( $n = 21$ ) and outdoor ( $n = 12$ ) sow herds with the same feeding and vaccination programs and genetics were evaluated in the same time frame (Akos and Bilkei, 2004). In this study, a higher proportion of sows were culled for locomotor problems from outdoor compared to indoor herds (39% vs. 25% of removals;  $P < 0.05$ ). Overall, sows remained in indoor herds longer than in outdoor herds ( $P < 0.01$ ;

Akos and Bilkei, 2004). In another study comparing finishing pigs raised in organic pen systems with deep bedding and indoor and outdoor access at all times compared to conventional indoor pens with bare concrete only, no differences were detected in gait scores evaluated using a 4-point subjective scoring system at 18 and 26 weeks of age ( $P > 0.05$ ; Etterlin et al., 2015). However, pigs in organic pens had higher incidence and prevalence of osteochondrosis, which was scored at slaughter on a scale of 0 to 5 in multiple locations in the shoulder, elbow, stifle, and hock joints. The sum of the osteochondrosis scores in the hock joint and whole pig were significantly associated with gait scores at week 26 ( $P < 0.05$ ) despite differences in gait score between housing types being non-significant. The authors hypothesize that pigs in an organic housing system can tolerate a higher pain threshold (caused by increased osteochondrosis) without showing signs of pain when walking due to being more active and having stronger muscles, bones, and tendons. This study did occur on only one farm, so it would be valuable to see if results were replicable on other farms (Etterlin et al., 2015).

#### **1.4.2 Comparison of Pen and Stall Systems**

Incidence of lameness has been compared between pen and stall gestation housing within conventional production systems. Harris et al. (2006) compared gait of gilts housed in stalls or small group pens containing static groups of four gilts per pen. The floors of both stalls and pens were fully slatted with no bedding, and the pens contained individual feeding stalls with no backs. Gait was scored on a scale of 0 to 5 as the gilts moved from gestation to farrowing facilities. Gilts housed in pens tended to have a higher (less favorable) gait score (0.67) than gilts housed in stalls (0.29;  $P < 0.1$ ). Statistical significance was not reached likely due to the small sample size of this study; there were

only 14 gilts in stalls and eight pens. Pen was the experimental unit used; therefore, the gait scores of the four gilts in each pen were averaged to obtain eight data points representing the pen treatment (Harris et al., 2006). Calderón Díaz et al (2014) found that sows housed in a large dynamic group pen ( $n = 43$ ) were more likely to be lame than sows housed in individual stalls ( $n = 42$ ; odds ratio = 4.51;  $P < 0.01$ ). Sow was the experimental unit in this study as the pen size was large, and only one pen was used. The stalls were fully slatted, whereas the pen had solid nesting areas in addition to a central slatted walking and dunging area containing two electronic sow feeders. Lameness was scored on a scale of 0 to 5 as the sows (mean parity =  $3.2 \pm 0.99$ ) moved from gestation to farrowing. A lame classification (score  $\geq 2$ ) was given to over 74% of pen-housed sows and 33% of stall-housed sows. Walking on slats, which is required to access feed and water, is believed to have contributed to the increased incidence of lameness in group-housed sows. Additionally, the authors believe the dynamic groups contributed to increased lameness as aggression increased each time the group makeup changed due to establishment of new dominance hierarchies. This hypothesis was supported by group-housed sows having increased body lesions than stall-housed sows upon moving to farrowing (Calderón Díaz et al., 2014). However, Harris et al. (2006) also observed more body lesions on gilts in small static pens than gilts in stalls at the end of gestation. Knox et al. (2014) compared lameness and body and head lesion scores between mixed-parity sows ( $n = 1,436$ ) individually housed in stalls or mixed between 3 and 7 days after breeding, between 13 and 17 days after breeding, or on or after day 35 after breeding. These sows were observed throughout gestation, and the observations were split into two periods. The first period consisted of the first 12 days after mixing (or post-breeding for

sows in stalls) where sows were observed every three days while the second period consisted of the remainder of gestation until moving to farrowing at 110 days of gestation where sows were observed every two weeks. Lameness was scored as a binary trait while lesions were assessed using a 4-point scale. Lameness was lower in sows housed in stalls compared to pens regardless of mixing time during both periods ( $P < 0.05$ ), except for sows mixed 3 to 7 days after breeding during period 1. Incidence of lameness was higher in sows mixed 35 days after breeding during period 1 ( $P < 0.05$ ) compared to all other groups; however, they were further along in gestation at the time of period 1 measurements than the sows in other groups. Incidence of lameness increased in the group mixed between 3 and 7 days after breeding and decreased in the group mixed 35 days after breeding ( $P < 0.05$ ) between periods 1 and 2, but no changes were observed in sows housed in stalls or mixed 13 to 17 days after breeding. During period 2, sows mixed 3 to 7 and 13 to 17 days after breeding had a higher incidence of lameness ( $P < 0.05$ ) than sows housed in stalls, with sows mixed 35 days after breeding intermediate (Knox et al., 2014). Like in Calderón Díaz et al. (2014), both head and body lesion scores were lower in sows housed in stalls compared to sows housed in pens regardless of mixing time in both periods 1 and 2 ( $P < 0.05$ ; Knox et al., 2014). Mixing time influenced body and head lesions in sows housed in pens during period 1, with greater lesions occurring when mixing occurred earlier. Mixing at days 3 to 7 resulted in the greatest lesion scores followed by days 13 to 17 and then day 35 (each group significantly different from others at  $P < 0.05$ ). However, during period 2, there were no differences between mix times (Knox et al., 2014).

Conversely, older studies comparing individual and group housing in young boars have demonstrated positive effects of group housing rather than individual housing on feet and leg soundness (Tonn et al., 1985; Hacker et al., 1994). In Hacker et al. (1994), young boars were housed in pens of four pigs until 30 kg, when they were scored on a scale of 0 to 4 for 13 leg structure traits and on a scale of 0 to 7 for general locomotion and placed in housing treatments of either individual pen or group pen of eight boars. Scoring was completed at the end of the test period, when the boars weighed approximately 110 kg. Group housed boars had significantly lower (more favorable) scores for front legs turned out ( $P < 0.01$ ), rear pastern angle (referred to as “down at pasterns” in this study;  $P < 0.01$ ), and hock angle ( $P < 0.05$ ). No differences between housing systems were observed for general locomotion or the other ten structural traits (Hacker et al., 1994). Fredeen and Sather (1978) reported increased damage to the cartilage and synovial fluid of joints with increased time in confinement in young boars, which seemed to be more associated with time rather than weight though weight tended to increase with increased time in confinement. While not statistically significant, greater joint damage occurred when young boars, gilts, and barrows were in individual housing ( $2.3 \text{ m}^2/\text{pig}$ ) compared to group housing ( $1.0 \text{ m}^2/\text{pig}$ ), despite having more space/pig available. However, joint damage was not associated with crooked, swollen, or crippled forelegs or weak or crippled hindlegs (Fredeen and Sather, 1978). While lameness was not assessed in the study, Marchant and Broom (1996) did find that parity 7 and 8 sows housed in stalls ( $n = 8$ ) required more time to lay down than sows housed in groups ( $n = 24$ ;  $P < 0.001$ ). Stall-housed sows also had smaller muscles involved in locomotion in proportion to total body weight than group-housed sows, some of which were

significantly associated ( $P < 0.05$ ) with speed of all or part of the lying down process. While time to lay down in this study could have also been affected by sows in pens having straw bedding while sows in stalls were on bare concrete (Marchant and Broom, 1996) and a small sample size, this suggests that leg weakness may also occur in sows as a result of decreased exercise and muscle use; however, it does not seem to manifest in observable locomotion problems nearly as much as in growing pigs (Elliot and Doige, 1973; Fredeen and Sather, 1978). Marchant and Broom (1996) also discovered that body length and height to the point of the shoulder were associated with total time required to lay down by sows in stalls ( $n = 30$ ;  $P < 0.001$ ), with larger sows requiring more time. The authors believe this is due to increased difficulty maneuvering a larger body within the confines of the stall potentially due in part to commercial stalls at the time being inadequately sized to accommodate larger sows. In group housed sows ( $n = 24$ ), no associations were observed between body size traits and time required to lay down except body length was associated with time required to complete stage 1 of the laying down process ( $P = 0.01$ ), which includes the transition from standing to a full kneel on the front legs (Marchant and Broom, 1996).

Exercise has been evaluated as a remedy for muscular, skeletal, and joint weakness associated with close confinement. Schenck et al. (2008) assessed effects of exercising gilts ( $n = 51$ ) between day 35 and 110 days of gestation. Gilts that were in good body condition and not lame were allotted to either a control group that was not exercised, a low exercise group that traveled 122 m/d for five d/wk, or a high exercise group that traveled 122 m/d for two d/wk and 427 m/d for three d/wk after two wk of gradually working up to 427 m/d. Lameness was scored 14 d before breeding, at d 35 of

gestation when treatments began, at d 56, 84, and 110 of gestation, and at weaning. No differences in lameness were observed between treatment groups at any time point ( $P > 0.1$ ; Schenck et al., 2008); however, it was unclear as to whether control gilts were moved out of their stalls for lameness detection or not. Outside of the specified lameness scoring times, the authors state that more injuries and lameness were observed in gilts exercised daily, but this was likely due to greater ease in identifying issues when asking gilts to move out of their stall compared to observing them in the stall. Osteoclast activity did not appear to be affected by treatment ( $P > 0.1$ ) as measured by carboxy-terminal telopeptide of type I collagen in blood samples taken at 14 days prior to breeding, d 35, 54, and 110 of gestation, and at weaning. Weights of 11 muscles dissected from gilts slaughtered three d after weaning did not differ between treatments ( $P > 0.1$ ), and there were also no differences in the severity of articular cartilage damage ( $P > 0.1$ ). Density of six bones was measured via both computed tomography (CT) and dual energy x-ray (DEXA) scans. Results from the CT scan found the low exercise group had greater bone density ( $P < 0.04$ ) for three of the six bones than the control group while the high exercise group also had greater bone density ( $P < 0.05$ ) for two of these same bones compared to control. However, the DEXA scan did not identify any differences in bone density between treatments ( $P > 0.1$ ). Breaking force, shear force, and cortical bone thickness were measured on four bones. For two bones, breaking force was greatest in the low exercise group compared to control ( $P < 0.05$ ). For one bone, breaking force was greater in both the low and high exercise groups compared to control ( $P < 0.05$ ), and no differences between treatments were observed for the final bone ( $P > 0.1$ ). No differences between treatments were observed for shear force or cortical bone thickness ( $P > 0.1$ ).



Hoof lesions and bruising were scored after slaughter, and each hoof was given a single lesion score. The right front foot tended to have a more severe foot lesion score on average in the high exercise group compared to control ( $P < 0.1$ ) with the low exercise group intermediate and not different from the others ( $P > 0.1$ ), but no differences between treatments were observed for the other three feet ( $P > 0.1$ ). Exercise decreased the total time taken to lay down during lactation; the control group required longer to lay down than both exercise groups ( $P < 0.02$ ), and the low exercise group tended to take more time to lay down than the high exercise group ( $P = 0.08$ ; Schenck et al., 2008). This is similar to what was observed by Marchant and Broom (1996) and strengthens their hypothesis that muscular strength is decreased by lack of exercise and is manifested in greater time required to lay down. However, Marchant and Broom (1996) observed increased muscle weights in proportion to body weight in group-housed sows (which exercised within their pen) compared to stall-housed sows, whereas exercise did not increase muscle weight in the study by Schenck et al. (2008). However, in Schenck et al. (2008) muscular weight was not compared as a proportion to body weight, which may be the reason for the difference in results. Finally, live litter birth weight, number of pigs weaned, and weaning weight adjusted for age at weaning were greater in the high exercise group compared to the control and low exercise groups ( $P < 0.05$ ). Prewaning mortality was decreased in both exercise groups compared to control ( $P < 0.05$ ) and might be related to greater muscle control in laying down as exercised sows were able to lay down faster, possibly reducing piglet crushing (Schenck et al., 2008).

In a smaller study of growing boars ( $n = 12$ ) between 22.3 and 90 kg of bodyweight, exercise had a favorable effect on front leg conformation (Perrin and

Bowland, 1977). Boars housed in individual pens during the study and allotted to a control group with no exercise, a low exercise group which walked on a treadmill at two km/h, or a high exercise group which walked on a treadmill at four km/h. Both exercise groups were walked three times per wk and started with three 10 min walking periods alternating with ten min rest periods and worked up to six 10 min walking periods alternating with ten min rest periods. Leg conformation and gait were scored at wk 6 and 10 of the study, and single scores were assigned for the forelegs and hindlegs. Boars that were not exercised showed more foreleg abnormalities than boars in both exercise groups ( $P < 0.05$ ), such as bowlegs and poor carpus flexion. There were no differences in hindleg scores between groups ( $P > 0.1$ ). Boars were slaughtered at 90 kg of body weight to assess cartilage lesions and bone composition. Exercise did not affect mean lesion scores for joint cartilage ( $P > 0.1$ ), but cartilage scores at the distal humerus ( $r = 0.43$ ;  $P < 0.05$ ) and proximal radius-ulna ( $r = 0.57$ ;  $P < 0.01$ ) were correlated with foreleg scores. Bone composition did not differ between treatments ( $P > 0.1$ ), suggesting exercise did not influence bone mineralization (Perrin and Bowland, 1977).

Sows housed in stalls were less likely to have overgrown heels and cracks in the wall, white line, sole, and heel-sole junction than sows housed in pens with ESF at day 110 of gestation ( $P < 0.05$ ) in a study by Anil et al. (2007). However, Calderón Díaz et al. (2014) found that sows housed in stalls had a greater risk of white line cracks, horizontal wall cracks, and elongated dew claws ( $P < 0.05$ ) five days prior to farrowing, though stalls tended to be advantageous for reduced odds of heel overgrowth and erosion ( $P < 0.07$ ). At weaning, sows housed in stalls still tended to have more white line cracks than sows housed in pens ( $P = 0.08$ ), though sows housed in pens had a tendency for increased

vertical wall cracks ( $P = 0.08$ ). Regional differences in management could have influenced results, as Anil et al. (2007) was conducted in Canada and Calderón Díaz et al. (2014) was conducted in Ireland. Flooring and pen layout differences could have also contributed to these conflicting results. In both studies, stalls were fully slatted, whereas pens were fully slatted in the study by Anil et al. (2007) but had solid nesting areas in the study by Calderón Díaz et al. (2014). Calderón Díaz et al. (2014) hypothesized that decreased white line cracks in pen-housed sows was due to their ability to move away from dunging areas to nesting areas that were clean and dry. This difference in floor hygiene may not have been present in the study by Anil et al. (2007) as both pens and stalls were fully slatted and there was no mention of nesting areas in the pens. Borderas et al. (2004) demonstrated that the claws of dairy cows absorb water and soften at the white line, sole, and wall when soaked in water. Absorption occurred rapidly, as the claws absorbed 30% of the total water absorbed in a 24-hour period during the first hour and 50% during the first four hours. Some evidence of a linkage between claw softness and foot lesion severity existed. Foot lesions were scored, and hardness was measured at three points on the sole and one point on the claw wall in the same 39 cows 30 days apart in both May and June. In May, there was a small, negative correlation between sole hemorrhage severity and average sole hardness measured at three points on the sole ( $r = -0.37$ ;  $P < 0.05$ ). In June, small, negative correlations were present between white line hemorrhage severity and sole hardness measured at the sole-bulb junction ( $r = -0.43$ ;  $P < 0.05$ ), heel erosion severity and average sole hardness measured at three points ( $r = -0.39$ ;  $P < 0.05$ ), and sole ulcer severity and claw wall hardness ( $r = -0.36$ ;  $P < 0.05$ ). A larger negative correlation was observed between average sole hardness in May and heel

erosion severity in June ( $r = -0.56$ ;  $P < 0.01$ ). Cows with a total lesion score  $> 3$  had significantly softer soles (average of three points on the sole) than cows with a total lesion score of 0. However, claws were significantly softer in May than in June at all points ( $P < 0.01$ ), while sole hemorrhage and the sum of all lesion severity scores decreased between May and June ( $P < 0.05$ ). While this does not support the hypothesis that soft claws are associated with more severe lesion scores, it is possible that this improvement could be due to the foot trimming that occurred at the same time as measurements in May (Borderas et al., 2004).

### **1.4.3 Pen Management**

There were no differences in toe or dew claw length, wall cracks, or heel overgrowth and erosion between sows in free access stalls with static groups or pens with ESF and dynamic groups (Pluym et al., 2011). While dynamic sow groups did not increase lesion severity in Pluym et al. (2011), regrouping developing gilts was shown to increase foot lesion severity when three of six gilts in the pen were switched monthly from eight to ten months of age (Olsson et al., 2016). Specifically, gilts that were regrouped had more severe soft horn lesion scores ( $P = 0.014$ ), hard horn lesion scores ( $P = 0.005$ ), and total lesion scores ( $P = 0.004$ ) at 11 months of age than gilts that did not experience regrouping (Olsson et al., 2016). However, this difference may be due to fewer females per pen and a higher proportion of novel individuals in the pen following regrouping than in Pluym et al. (2011).

### **1.4.4 Flooring and Stocking Density**

Among sows housed in group pens in conventional production systems, pen flooring has been shown to influence risk of lameness. In a review by Spooler et al. (2009), it was concluded that poor floor quality, including dirty/slippery floors, and poor slat integrity (e.g., sharp or damaged edges) increased likelihood of injury and lameness. Spooler et al. (2009) also concluded that bedding reduced foot lesions and frequency of abnormal gait. Heinonen et al. (2006) assessed the prevalence of lameness in 21 sow herds in Finland and explored potential causative variables. All animals near the time of breeding (i.e., gilts selected for breeding, sows between weaning and breeding, lactating sows at least five days post-partum, and sows mated within the last 30 days) were determined to be sound, slightly lame, or severely lame and the cause of lameness diagnosed. In total, data from 646 animals was used in the analysis; 8.8% of these sows were lame (either slightly or severely lame) and 3.4% of all sows were severely lame. Slatted vs. not slatted floors was the greatest risk factor for developing lameness as it had a significant impact on both overall lameness and severe lameness in both univariate and multivariate analyses ( $P < 0.05$ ). From the fit of a multivariate model for lameness, the odds were 2.0 for slatted vs. not slatted floors. In a multivariate model for severe lameness, the odds were 3.7 for slatted vs. not slatted floors. Breed also reached significance ( $P < 0.05$ ) in both univariate and multivariate analyses for overall lameness. A significant area per animal by confinement in a stall for up to 30 days post-mating interaction for overall lameness in sows was detected in the univariate analysis (Heinonen et al., 2006).

Andersen and Bøe (1999) compared movement disorders between sow farms that used straw bedding ( $n = 7$ ) compared to farms without straw bedding ( $n = 7$ ). The sows

on all farms in this study were group housed in dynamic groups of at least ten sows each and fed twice a day in individual feeding stalls. Fresh straw bedding was added once a day, and 0.3 to 0.6 m of straw covered the entire pen area except for the feeding stalls. The pens without straw were partly covered with a small amount of sawdust. Ten to 16 sows at each farm were scored for movement disorders on a scale of 1 to 3 at two separate visits spaced apart by at least four weeks. Each visit occurred one to two weeks after new sows were introduced to the pens. Herds with straw bedding had lower (more favorable) movement disorder scores than herds without straw bedding (1.2 vs. 1.4, respectively;  $P = 0.01$ ; Andersen and Bøe, 1999).

Devillers et al. (2019) assessed the effects of varying slat and gap widths on the gait of sound gilts and lame sows. Gait was scored on a scale of 0 to 4, with 0 being normal gait and 4 being non-ambulatory. Twelve Yorkshire x Landrace animals were selected for the study in each group; sound gilts consisted of nulliparous or primiparous females with a gait score of 0, and lame sows consisted of primiparous or multiparous females with a gait score between 1 and 3. On average, lame sows were older and larger than sound gilts. These groups were chosen because their gait was expected to be the most impacted by flooring differences due to having smaller feet in the case of gilts or already being lame in the case of lame sows. Three slat widths (85, 105, and 125 mm) and three gap widths (19, 22, and 25 mm) were tested in a factorial treatment structure, giving nine experimental treatments. Control solid concrete floors were also tested. Video recordings were taken of each animal walking through the test corridor on their assigned treatment floors. Gait kinematics were analyzed for the following parameters: walking speed, stride length, swing time (time the foot was in movement off the floor), stance

time (time when the foot was touching the floor), foot height at the maximum reached during the swing, the angle mean and amplitude for the carpal (fore leg) and tarsal (hind leg) joints during the swing and stance periods, and the angle of the animals' back. Parameters with significant effects ( $P < 0.05$ ) were related to back angle, foot height, stride length, and carpal and tarsal joint angle amplitudes. In sound gilts, stride length of the rear limb was significantly ( $P = 0.021$ ) affected by the slat. Gap width had a significant effect on back angle ( $P = 0.04$ ) of sound gilts when slats were in a perpendicular orientation. Walking on floors with 25 mm gaps resulted in a more arched back than when gap width was 19 or 22 mm. The authors hypothesized changes in stride length and back angle could be coping mechanisms for lameness on non-ideal floor conditions. Sound gilts had higher ( $P < 0.05$ ) front foot elevation when walking on 105 mm slats compared to 125 mm slats in both orientations. Conversely, gap width had a greater effect on foot height of lame sows; front foot height increased ( $P = 0.015$ ) when walking on 25 mm gaps compared to 19 mm gaps on perpendicular oriented slats. Effects on joint angle amplitudes were quite variable between sound gilts and lame sows and between the swing and stance phases of the stride. In sound gilts, the carpal joint angle amplitude was increased (more flexion) during the stance phase on 85 mm slat widths and 22 mm gap widths in the parallel orientation ( $P < 0.05$ ). In lame sows, both carpal and tarsal joint amplitudes showed increased flexion ( $P < 0.05$ ) during the swing phase on perpendicular 125 mm slats, while tarsal joint amplitudes showed increased flexion ( $P = 0.022$ ) during the stance phase on perpendicular slats with 22 mm gaps. Increased flexion in these joints could potentially indicate an improved ease of movement. Additionally, more front limb parameters were significantly or suggestively ( $P < 0.1$ )

affected than hind limb parameters (13 vs. 7 parameters, respectively). This is to be expected as the front limbs are closer to the center of gravity and bear a greater proportion of the weight. Overall, more floor type effects were observed in sound gilts than lame sows, potentially indicating greater sensitivity to floor characteristics. While these results are conflicting at times and very difficult to interpret, the authors believe smaller (19 and 22 mm) gap widths and larger (105 and 125 mm) slat widths may be conducive to improving ease of walking, though other factors, such as behavior, performance, incidence of lameness, and cleanliness and manure drainage are also important and should be assessed (Devillers et al., 2019).

Rubber slat mats have also been evaluated for their effect on lameness in gestating sows. Calderón Díaz and Boyle (2014) housed sows in groups of four in either pens with bare concrete slats or rubber mats in the common area of gestation pens that also contained four free access stalls. The pens with rubber mats retained half the number of slats as the bare concrete pens. Lameness was scored on a scale of 0 to 5, and each sow was classified as lame (score  $\geq 2$ ) or not lame (score  $\leq 1$ ) at five time points during gestation. Lameness was not affected by flooring ( $P > 0.05$ ). While there were not differences in lameness status, sows spent more time in the group area ( $P < 0.01$ ) and more time in a laying posture while they were there ( $P < 0.05$ ) when rubber mats were included, indicating they preferred to lay on the softer surface. There was no association between flooring type and pen cleanliness in the group area or manure on the body of the sows ( $P > 0.05$ ); however, the feeding stalls in the pens with rubber mats did have an increased risk of dirtiness (OR = 1.7;  $P < 0.01$ ) and wetness (OR = 2.5;  $P < 0.01$ ). This is likely because sows in pens with rubber mats were using the group area for laying down



and the feeding stalls for dunging, whereas sows in pens with bare concrete were using the feeding stalls for laying and the group area for dunging (Calderón Díaz and Boyle, 2014). Elmore et al. (2010) assessed the effects of rubber slat mats in a similar study, except the rubber mats were placed inside the free access stalls rather than in the group area. Pen structure was similar as pens consisted of four feeding stalls with solid concrete flooring and a slatted group area for exercise and dunging. Each pen housed four multiparous sows, and a total of 128 sows were used in the study. Lameness was scored on day zero and day ten on a scale of 0 to 5 that took both standing posture and gait into account. There was no overall difference in lameness scores for sows housed in pens that included rubber mats and sows in pens with bare concrete only ( $P = 0.7$ ; Elmore et al., 2010). One might suspect this to be due to the short study time frame of only 10 days; however, 10 days was enough to result in an increase in lameness scores between day 0 and day 10 ( $P < 0.01$ ) in both rubber mat and bare concrete pens (Elmore et al., 2010). Similar to what was observed in Calderón Díaz and Boyle (2014), sows appeared to prefer laying on the rubber mats rather than concrete (Elmore et al., 2010). Pen locations used by the sows differed between flooring treatments ( $P = 0.008$ ). Sows in concrete only pens spent more of their resting time in the group area of the pen than sows in pens with rubber mats ( $P < 0.05$ ), while sows in pens with rubber mats spent more of their resting time in the stalls where the mats were than sows in pens without mats ( $P < 0.05$ ; Elmore et al., 2010).

Rubber flooring has also been evaluated for beneficial effects on foot lesion severity. Calderón Díaz et al. (2013) housed gestating sows in fully slatted pens with either concrete flooring or concrete covered with rubber slat mats from breeding to day

110 of gestation during their first two parities. Sows on rubber slat mats had an increased likelihood of having lesion scores higher than the median for elongated toes and heel-sole cracks mid-way through gestation in both parity 1 and 2, a greater risk of wall crack scores greater than the median mid-way through parity 1 gestation, and an increased risk of white line crack scores greater than the median mid-way through parity 2 gestation ( $P < 0.01$ ; Calderón Díaz et al., 2013). Bos et al. (2016) also housed sows in pens that were either bare concrete or covered with rubber in part of the solid lying area and the fully slatted area from 28 days after insemination until day 108 of gestation through three parities. Less severe scores for heel overgrowth and erosion ( $P = 0.041$ ) and heel-sole cracks ( $P = 0.01$ ) were observed in sows housed on rubber floors mid-way through gestation. Vertical wall cracks were more severe in sows housed on rubber floors than bare concrete ( $P = 0.048$ ). Sows housed on rubber floors tended to have more severe scores for white line cracks ( $P = 0.057$ ) and elongated toes ( $P = 0.081$ ). Interestingly, by weaning, the sows housed on rubber flooring had less severe scores for white line cracks ( $P = 0.024$ ) and elongated toes ( $P < 0.001$ ) and tended to have less severe scores for vertical wall cracks ( $P = 0.081$ ; Bos et al., 2016). Despite somewhat conflicting results for effects on foot lesion severity, both studies demonstrated a positive effect of rubber on locomotion. Specifically, sows housed on rubber had a significantly reduced risk of lameness in both parities 1 and 2 ( $P < 0.01$ ; Calderón Díaz et al., 2013) and a more favorable locomotion score on day 108 of gestation ( $P < 0.001$ ; Bos et al., 2016).

Flooring type in the farrowing crate also influenced foot lesions, as sows housed in farrowing crates with cast iron floors had a lower likelihood of heel overgrowth and erosion ( $P < 0.01$ ) and heel-sole cracks ( $P < 0.01$ ) and tended to have reduced horizontal

wall cracks ( $P < 0.08$ ) than sows housed in farrowing crates with slatted steel floors during lactation (Calderón Díaz et al., 2014). Heel-sole cracks, vertical and horizontal wall cracks, and elongated/injured dew claws were more severe at weaning than five days prior to farrowing. The authors hypothesized these effects were due to increased void area compared to solid area in farrowing versus gestation and in slatted steel versus cast iron (Calderón Díaz et al., 2014). Farrowing crate flooring type also affected the prevalence of foot lesions in piglets (Quinn et al., 2015b). The risk of sole erosion was increased by pens with metal slats under the sow ( $OR = 1.93$ ) and pens with a concrete solid area for piglets ( $OR = 1.79$ ) compared to pens with plastic slats throughout and a plastic solid area for piglets. Pens with metal flooring also increased the risk of coronary band injury compared to pens with plastic flooring ( $OR = 4.25$ ). However, metal slats under the sow with plastic piglet areas reduced the risk of sole bruising ( $OR = 0.32$ ) compared to pens with plastic slats in both sow and piglet areas (Quinn et al., 2015b).

Flooring has also been shown to impact the severity of foot lesions in boars and growing pigs (Newton et al., 1980; Brennan and Aherne, 1987; Mouttotou et al., 1999; Gillman et al., 2009; Wang et al., 2018). Wang et al. (2018) assessed foot lesions in boars housed in either individual stalls with slatted floors or individual pens with solid floors. Flooring type influenced all eight types of foot lesions scored ( $P < 0.01$ ). Boars housed in stalls with slatted floors had a decreased likelihood of heel overgrowth and erosion, white line cracks, horizontal wall cracks, vertical wall cracks, and heel-sole cracks, whereas boars housed in pens with solid floors had a decreased likelihood of elongated toes and dew claws (Wang et al., 2018). In growing pigs, woven wire flooring resulted in a higher average foot pad lesion score (average score of all four feet) than plastic-coated expanded

metal flooring at 28 d post-weaning ( $P < 0.01$ ; Brennan and Aherne, 1987). When comparing steel, plastic, concrete, and aluminum slatted floors during the grow-finish phase only (23 – 98 kg of bodyweight), hoof length (measured from the point of each toe to the coronary band) and sole length (measured from the toe tip to the posterior end of the heel) were longest at slaughter in pigs housed on plastic floors, followed by aluminum, steel, and then concrete with each floor type being significantly different from all others ( $P < 0.01$ ; Newton et al., 1980). Sole width (measured at the widest part of each toe) was narrower in pigs housed on concrete floors compared to all other floor types ( $P < 0.01$ ). Floor type did not have a significant effect on overall pad condition score ( $P > 0.05$ ), scored on a scale of 1 to 5. Hoof cracks were more severe in pigs housed on concrete for both inner and outer toes than pigs housed on all other floor types ( $P < 0.01$ ), while the outer toes of pigs housed on steel had more severe hoof cracks than pigs housed on plastic or aluminum ( $P < 0.01$ ; Newton et al., 1980). Mouttotou et al. (1999) compared five group pen flooring types for their effect on foot lesion incidence evaluated at slaughter on finishing pigs. These farms had floor types of either solid concrete, solid concrete with straw bedding  $< 10$  cm thick, solid concrete with straw bedding  $> 10$  cm thick, partially slatted, or fully slatted. Solid concrete floor served as the control. The types of foot lesions that were evaluated were toe, sole, and heel erosions, heel flaps, white line lesions, false sand cracks, wall separation, wall penetration, heel corrugation, overgrown hooves, and unequal claw size. The overall average prevalence of foot lesions on these farms was 93.8% with a range of 79.4% to 100.0%. Compared to solid concrete floor, pigs housed on partially slatted floors had a significantly higher prevalence of heel erosions, white line lesions, and wall separations while pigs housed on completely slatted

floors had a significantly higher prevalence of sole erosion and heel flaps ( $P < 0.01$ ).

Slats increase the uneven distribution of pressure on the weight-bearing surface of claws, which may be why pigs living on slats had increased incidence of some foot lesions.

Straw bedding produced mixed results compared to bare solid concrete. Toe erosion and false sand cracks were increased in pigs housed with straw bedding regardless of thickness ( $P < 0.01$ ). Bedding that was  $> 10$  cm thick also resulted in increased incidence of wall separations ( $P < 0.01$ ) compared to bare, solid concrete, while there was no difference in wall separation incidence between bare, solid concrete and solid concrete with bedding  $< 10$  cm thick. However, incidence of sole erosion was decreased in pigs housed with bedding regardless of thickness compared to bare, solid concrete ( $P < 0.01$ ).

Reduced incidence of heel erosion and heel flaps were also observed in pigs housed on solid concrete with bedding  $< 10$  cm thick ( $P < 0.01$ ), whereas solid concrete with bedding  $> 10$  cm thick was not significantly different than bare, solid concrete. Straw provides a soft surface that reduces the pressure on the weight bearing surface of the foot. However, claws do not wear down quickly enough on soft surfaces, such as straw, which can cause horn overgrowth and a reshaping of the claw and therefore pressure distribution, likely causing the shift from heel and sole lesions to wall lesions.

Additionally, straw gets wet and has an alkaline pH from absorbing animal excretions, which can soften the hoof, making it more susceptible to damage (Moultotou et al., 1999). However, a weakness of this study was that only one finishing unit had bare, solid concrete floors, which was the control treatment, and there was also only one finishing unit with totally slatted floors; results therefore may be confounded with other differences related to those particular units. However, Gillman et al. (2009) observed similar results,

and reported a higher prevalence of heel flaps and heel/sole bruising in six, eight, or 14 week old growing pigs on partially or fully slatted floors compared to solid concrete with bedding or soil, whereas deeply bedded solid concrete produced the highest incidence of toe erosion.

Jørgensen (2003) assessed the effects of three types of flooring - solid concrete floor without bedding, solid floor with plenty of bedding, and fully slatted floor - with two stocking densities - high (0.65 m<sup>2</sup> per pig) and low (1.2 m<sup>2</sup> per pig) - in a 3x2 factorial design on locomotion, conformation traits, osteochondrosis, and foot lesions in market hogs. A total of 300 pigs in five batches were used in this study. Pigs were placed in their respective housing treatments between 25 and 105 kg of body weight.

Locomotion and conformation traits were assessed on a scale of 1 to 4 prior to slaughter. Specific traits scored were stiff in front, stiff in rear, swaying hindquarters, buck-knees, standing under on hind legs, and upright pasterns and legs turned out on both the front and hind legs. Osteochondrosis was scored on a scale of 1 to 5 on the elbow and stifle joint and the distal ulna growth plate from the left side of the body after slaughter. Claw lesions were also scored on a scale of 1 to 5 on the left claws after slaughter. Specific claw lesions scored were overgrown claws, overgrown dew claws, excessive wear, side wall lesion, lesion on volar surface, lesion in white line, and heel lesion. Hardness of claws was also measured on the last batch using a Shore Durometer in four locations on the claw, cranial, lateral, and caudal on the top of the claw and volar on the bottom of the claw. Stocking density had a significant effect on legs standing under and legs turned out in the hind legs, with low stocking density being favorable ( $P < 0.05$ ). There was also a tendency for low stocking density to improve buck-knees and front legs turned out ( $P <$

0.1). There was an interaction between floor type and sex in which floor type affected front legs turned out in gilts ( $P < 0.05$ ) but not boars. Solid floor with straw was associated with the most favorable front legs turned out conformation, while bare solid floors produced the least favorable results. Slatted floors were intermediate and not significantly different from either of the other two floors. Floor type tended to affect hind legs standing under and stiff in rear ( $P < 0.1$ ). Solid floor with straw was significantly better for stiff in rear than either bare solid floor or slatted floor, while slatted floor was significantly worse for hind legs standing under than solid floor either with or without bedding. Looking at the overall sum of osteochondrosis scores, there was an interaction between floor type and sex in which floor type had a significant influence on boars ( $P < 0.05$ ) but not gilts. The bare solid floor resulted in less osteochondrosis than the solid floor with bedding and slatted floor. Stocking density did not significantly influence overall osteochondrosis score, but some significant associations did exist with individual locations where osteochondrosis was scored. Stocking density had a significant effect on white line lesions ( $P < 0.05$ ) and tended to affect side wall lesions ( $P < 0.1$ ). There was an interaction between stocking density and sex, where stocking density had a significant effect on overgrown claws in boars ( $P < 0.05$ ), but not gilts. Low stocking density was favorable in all cases, except distal ulna growth plate cartilage thickness. Floor type had a significant effect on volar surface lesions ( $P < 0.05$ ) and a marginal effect on white line lesions ( $P < 0.1$ ). The bare solid floor resulted in more severe lesions of both types than the solid floor with bedding and slatted floor, possibly due to urine and manure buildup that does not drain or get absorbed by bedding. However, the medial claws were harder in pigs housed on bare solid floors than pigs housed on slatted floors ( $P < 0.05$ ) with bedded

solid floor intermediate and not significantly different from either type of floor. There were no differences between floor types for lateral claw hardness. Stocking density did not influence claw hardness (Jørgensen, 2003).

Street and Gonyou (2008) assessed the effect of group size and space allowance on lameness in grow-finish pigs. They also found increased severity of lameness in a larger group size ( $P = 0.012$ ; group size of 108 pigs vs. 18 pigs per pen), but no effect of space/pig ( $P = 0.65$ ;  $0.52 \text{ m}^2$  vs.  $0.78 \text{ m}^2$  per pig). However, there was an interaction effect ( $P = 0.04$ ) between group size and space/pig in which crowding increased lameness in large groups but decreased lameness in small groups. Neither group size nor space allowance influenced the percentage of pigs that received medication to treat lameness or were removed due to lameness ( $P > 0.2$ ). The authors hypothesize that group size impacted lameness because larger pens are required to house larger groups, providing more space to run; running can cause injuries due to feet getting caught in slats and collisions with walls and other pigs. Additionally, behavioral observations suggested increased posture changes occurred in pigs housed in larger groups compared to smaller groups, and injuries could occur during this process (Street and Gonyou, 2008).

#### **1.4.5 Hoof Trimming**

Functional hoof trimming is routinely practiced in dairy herds (Stoddard and Cramer, 2017) as a means of reducing lameness and hoof lesions by correcting horn overgrowth and recreating even weight bearing across the hoof (Shearer and van Amstel, 2001). Tinkle et al. (2017) assessed the effects of functional claw trimming in 52 sows that had elongated toes on sow gait. Before trimming, sows had an average claw length of 6.7 cm and an average dewclaw length of 6.6 cm. Claws were trimmed to a target length



of 5.5 cm, while dewclaws were trimmed to be even with the coronary band. The actual post-trimming measurements were 5.2 cm and 3.7 cm for claws and dewclaws, respectively. Claws were also shaped during trimming to provide a rounded edge and smooth, level sole. Sows were video recorded on both the left and right sides walking for 2.4 m before trimming and one and 48 hours after trimming. Changes were observed in gait parameters, implicating improvements in gait and locomotion after claw trimming. Stance duration and swing duration both decreased ( $P < 0.001$ ) in front and rear feet 48 hours after trimming, though the decrease in swing duration was observed in the front foot by one hour post-trimming. Total stride duration also decreased after trimming in both feet ( $P < 0.05$ ). Front stride duration was significantly decreased from pre-trim at 48 hours post-trim with one hour post trim not significantly different from either time point while significant decreases occurred between each time point for rear stride duration. This indicates the sows were able to walk at a quicker pace after trimming. Breakover duration, or the time between when the heel begins to lift to when the toe is no longer touching the ground, was reduced ( $P < 0.05$ ) for both front and rear limbs between each set of time points. This might diminish strain on joints and ligaments of the lower limbs and lessen the number of injuries as the sow can transition between the stance and swing phases with greater ease. The ratio of breakover:stride duration also decreased between pre-trimming and post-trimming ( $P < 0.05$ ), further indicating an easier, more efficient transition between phases. Stride length also decreased in the front limbs ( $P < 0.05$ ) at both one and 48 hours after trimming compared to pre-trimming. However, even though the sows did not travel as far in one stride on their front legs after trimming, velocity increased between pre-trim and 48 hours post-trim ( $P < 0.05$ ) as did stride frequency.

Decreased stride length on the front limbs may also be advantageous as keeping the limbs closer underneath the body could reduce incidence of slipping. The percentage of stride spent in the three-limb support phase decreased at 48 hours post-trim compared to the other two time points ( $P < 0.05$ ) in both the front and rear. As the sows are also walking faster, it means they are spending more time in the two-limb support phase. While gait and locomotion were improved by functional claw trimming, potential performance improvements and economic benefits were not assessed (Tinkle et al., 2017).

#### **1.4.6 Conclusions**

As animal welfare continues to receive increasing scrutiny by consumers, it is important that the industry adopt management practices that optimize both welfare and production. Minimizing lameness and conformation problems by employing associated management factors is critical to accomplishing this goal. Furthermore, the industry must transition from stall to pen gestation housing systems in response to consumer demand. Socialization within the pen and the necessity to walk to access feed and water provides increased opportunity for poor conformation to manifest into lameness. Studies have shown increases in lameness in pen-housed sows compared to stall-housed sows (Calderón Díaz et al., 2014; Knox et al., 2014), though there are potential benefits to increased exercise and movement in a pen environment, including increased muscle mass (Marchant and Broom, 1996), bone strength, and reproductive performance (Schenck et al., 2008). Stall housing was detrimental to conformation in young boars (Hacker et al., 1994). However, this needs to be assessed in sows. Further study is also needed to evaluate the effects of pen compared to stall housing on foot lesions as conflicting results have been reported (Anil et al., 2007; Calderón Díaz et al., 2014). Floor type, stocking

density, rubber mats, and other factors within pen systems have been studied for effects on lameness and foot lesions, but further study is still required to draw clear conclusions.

### **1.5 Nutritional Factors Influencing Conformation and Lameness**

Dietary energy, calcium, phosphorus, lysine, and microminerals have been evaluated for effects on conformation and lameness. In a study published in three parts, Calabotta et al. (1982a; 1982b) and Arthur et al. (1983) assessed the impacts of energy, calcium (Ca), and phosphorus (P) levels during gilt development. Gilts ( $n = 288$ ) were assigned to either *ad libitum* or 75% *ad libitum* feed intake and either 100 or 150% of NRC (1979) recommended levels of Ca and P. Calabotta et al. (1982a), focused on foot and bone measurements, foot lesions, and overall structural soundness scores taken at approximately 50 and 100 kg of bodyweight. A caliper was used to measure four lengths on the feet, distance from the heel-sole junction to the tip of the toe (horn length), width of the toe at the widest point (toe width), distance from the coronary band to the tip of the toe on the top of the foot (horn height), and distance from the proximal periphery of the pad to the tip of the toe (toe length). These measurements were used to calculate the percentage horn, toe volume, and base area. Length of the third metacarpal, ulna, third metatarsal, and tibia and circumference of the foreleg and hind leg were taken with a tape measure. Pads and hooves of each toe were scored for lesions on a scale of 0 to 3 while overall structural soundness was scored on a scale of 0 to 15. Toe measurements indicated toes of *ad lib* gilts were larger than those of 75% *ad lib* gilts when adjusted for age with most measurements reaching statistical significance ( $P < 0.05$ ). However, when measurements were adjusted for weight, nearly all measurements were no longer significantly different between energy levels. Only a few measurements were

significantly affected by Ca and P levels. In most cases where a significant difference occurred, the higher level of Ca and P was associated with the larger measurement. When comparing front and hind feet and inner and outer toes, significant differences existed in all measurements ( $P < 0.01$ ). Outside toes were generally larger than inside toes. Front toes were wider than hind toes, while hind toes had greater horn height than front toes. However, interactions existed. Some resulted from differences in magnitude of the differences, such as the difference between inside and outside toes was much greater in the hind than front toes for horn and toe length. Energy level had an effect ( $P < 0.05$ ) on volume and base area of all toes with the *ad lib* group associated with larger volume and area; however, with an adjustment for weight differences, most significant differences disappeared. Without a weight adjustment, increased minerals also resulted in increased toe sizes. Circumference of the fore and hind limbs and length of the ulna, tibia, and metatarsal were greater ( $P < 0.05$ ) in *ad lib* gilts as well as metacarpals at 100 kg of bodyweight only, though none of these effects remained significant after a body weight adjustment except the length of the tibia at the 50 kg and the circumference of the hind limb at 100 kg. Mineral level did not affect any bone measurements. Both inside and outside toe pads on the front foot had a higher incidence of lesions in gilts that were fed *ad lib*, but limited fed gilts had a higher incidence of front horn lesions. Severity levels were similar between the two groups, and no differences were observed between energy levels on the hind feet. Mineral level did not affect foot lesion incidence or severity, except the 150% mineral level was associated with a higher incidence of lesions on the front outside pad and horn at 50 kg of bodyweight. Average front outside toe and front foot scores were also more favorable for gilts fed at the 100% mineral level. Overall

structural soundness scores were not affected by energy or mineral level (Calabotta et al., 1982a). Calabotta et al. (1982b) reports conformation trait measurements obtained from photographs taken while the gilts in the study walked on a treadmill at approximately 50 and 100 kg, the same time points as other measurements were taken. Photographs were taken from the side and rear of the gilts at a rate of 24 frames per second for a period of five to seven seconds. Editing occurred to identify a set of frames that contained three successive walking cycles. Twelve structural traits were measured from the side view. Five were body size traits: torso length, distance from shoulder to arc point of the back, height of back arc, girth diameter (or body depth) at the back arc, and pig height at the back arc. Four traits were joint angles: front and rear pastern angles, hock angle, and knee angle at the point of maximum flex as the front leg is lifted in motion. The remaining three traits consisted of front and rear foot height when the foot is off the ground during the walking cycle and number of frames to complete one walking cycle as an assessment of walking speed. Five conformation traits were measured from the rear view: width at the widest point across the hams, distance of lateral tail movement, distance between the hocks, and deviation of the hock from the edge of the hams on both the left and right side as a measure of leg curvature. As expected, all body size traits, except distance to the arc point of the back, were larger in *ad lib* fed gilts ( $P < 0.05$ ) without adjusting for body weight. With a body weight adjustment, most of the energy level effects were no longer significant. In contrast, distance to the arc point of the back became significant ( $P < 0.01$ ) after adjustment at 100 kg of bodyweight; the *ad lib* group had a shorter distance to the arc peak. Front pastern angle was the only angle measurement significantly affected by energy level ( $P < 0.05$ ). This angle was smaller (more flex) in *ad lib* fed gilts and was

only significant at 50 kg of bodyweight. Foot height on neither the front nor the rear foot was impacted by energy level ( $P > 0.05$ ). Gilts fed *ad lib* took a greater amount of time to complete one walking cycle at 50 kg of bodyweight ( $P < 0.05$ ), but no differences were observed at 100 kg. Mineral levels did not affect side view measurements, except girth diameter at 50 kg, pig height at both time points and hind pastern angle at 100 kg; these effects were no longer significant after bodyweight adjustment. Deviations of the hock from the edge of the ham were the only rear traits affected by energy level. Differences were present for left deviation at 50 kg and both right and average deviation at 100 kg ( $P < 0.05$ ) only after a body weight adjustment. Mineral levels did not affect rear view traits. All traits except front pastern angle changed ( $P < 0.01$ ) between 50 and 100 kg of bodyweight. Size traits increased along with growth. Hock and pastern angle increased (rear leg became more post-legged) over time while knee angle at maximum flex decreased (more flex and greater movement). Both left and right hock deviations increased (Calabotta et al., 1982b). Arthur et al. (1983) reported results obtained by following these gilts ( $n = 259$ ) through three parities. After gilts reached 100 kg, all received the same feeding regimen. The same toe and leg measurements and foot and overall soundness scores performed in Calabotta et al. (1982a) were taken 21 d after weaning parities one to three. Front and hind feet and inner and outer toes differed for all measurements. However, many interactions were present between energy level, mineral level, foot (front or rear) and toe (inner or outer). Front horn and toes were longer in *ad lib* fed gilts with no differences in hind horn and toe length due to energy. Hind toes were longer and front toes were wider in the 150% mineral level group, but there were no differences in front horn and toe length or hind toe width due to minerals. Gilts fed *ad lib*

had taller front toes but shorter hind toes than limit fed gilts. Outer toes were larger than inner toes for all measurements on both the front and rear feet. The front toes were wider than the hind toes. The magnitude of the difference in width between the inner and outer toe was greater in the hind foot. The hind toes were longer than the front toes. Finally, the magnitude of the difference in length between the hind inner and outer toes was greater than in the front toes. Volume and area of the front inside and outside and hind inside toes were greater in sows fed *ad lib*. A mineral by energy interaction was present in the front ( $P < 0.05$ ) and hind ( $P < 0.1$ ) inside toes because gilts fed *ad lib* and at the 150% mineral level had a greater toe area than the other treatment combinations. Energy by foot, mineral by toe, and foot by toe interactions existed for toe volume and area and followed similar patterns as in the one-dimensional measurements. Horn length, toe width, toe volume, and toe area significantly increased linearly from parity 1 to 3 ( $P < 0.01$ ). Some limb measurements were significantly different between energy and mineral levels and parities; however, these differences were numerically small. Sows previously fed *ad lib* had a significantly greater circumference of the front ( $P < 0.1$ ) and hind ( $P < 0.05$ ) limbs. Sows fed at the 150% mineral level had longer ulna ( $P < 0.05$ ) and metacarpal ( $P < 0.1$ ) bones. There was an interaction between energy and mineral level for metacarpal length; sows previously limit fed at the 100% mineral level had shorter metacarpals than all other treatment combinations. Incidence and severity of pad and horn lesions were not significantly affected by previously fed energy levels, except lesion severity was greater ( $P < 0.05$ ) in hind outer foot pads of sows previously limit fed. Likewise, mineral levels did not influence lesion incidence and severity with just three exceptions; sows fed at the 150% mineral level had a lower ( $P < 0.05$ ) incidence of pad

lesions and higher ( $P < 0.05$ ) incidence of horn lesions on the front inside toe as well as a greater ( $P < 0.05$ ) severity of hind inside pad lesions. Front feet had fewer lesions than hind feet, and inner toes had fewer lesions than outer toes ( $P < 0.01$ ). A linear decrease of pad and horn lesions were observed across parities ( $P < 0.05$ ), except the hind outside pad was not affected by parity. Structural soundness scores were not impacted by previously fed energy and mineral levels (Arthur et al., 1983).

In a very similar study, Barczewski et al. (1990) also looked at the effects of different dietary energy and Ca and P levels during the gilt development period and followed the sows through three parities to observe potential extended effects of dietary treatment on conformation traits and sow survival. Gilts ( $n = 288$ ) were assigned treatments of *ad libitum* vs. 75% *ad libitum* energy intake and 100 vs. 150% NRC (1979) recommended levels of Ca and P. The experimental diets were fed from weaning at four to five wk of age until 100 kg of body weight. A common diet was fed throughout the remainder of the experiment. To obtain conformation trait measurements, sows were walked on a treadmill at five time points: approximately 50 and 100 kg of body weight (119 and 192 d of age) and approximately 21 days after weaning parities 1 to 3. Sows were filmed walking on the treadmill until three sequential walking cycles in a natural gait were obtained from both the side and rear, and objective measurements were taken from the film using a reverse projection screen. Twelve conformation traits were measured from the side view and five conformation traits were measured from the rear view. These traits were the same as those measured in Calabotta et al. (1982b). At the same time points, sows were also visually scored for structural soundness on a 15-point scale. There were no significant interactions between energy and Ca-P levels for any of



the traits measured ( $P > 0.05$ ). When measurements from each of the five time points were averaged, all body size traits, except distance from shoulder to arc, were larger for gilts fed *ad libitum* ( $P < 0.05$ ). However, there was an energy by time interaction for girth diameter ( $P < 0.01$ ) as the magnitude of the effect decreased over time. Higher Ca and P intake also resulted in a longer torso ( $P < 0.05$ ) and a greater height of the back arc initially but not by the end of three parities as demonstrated by a significant interaction effect with time ( $P < 0.05$ ). Front pastern angle was smaller across all time points in gilts fed *ad libitum* ( $P < 0.05$ ), while no consistent differences were observed in the rear pastern angle. Hock angle tended to be smaller in limit-fed females ( $P < 0.1$ ), and no differences were observed for knee angle at the point of maximum flex. Calcium and phosphorus levels did not affect leg angles. There was a significant interaction in rear foot height between Ca-P level and time ( $P < 0.05$ ) in which gilts fed higher levels of Ca and P raised their rear foot higher during motion at 119 and 192 d of age and after parity 1 weaning but did not raise their rear foot as high as gilts fed lower levels of Ca and P after parity 2 and 3 weaning. Gilts fed *ad libitum* required more time to complete a walking cycle ( $P < 0.05$ ), and therefore, walked slower than limit-fed gilts. Distance between hocks was greater for *ad libitum* fed gilts at all time points except after parity 2 weaning. The deviation of the hock from the edge of the ham on the left side was greater for limit-fed gilts ( $P < 0.01$ ), but no differences were observed for the deviation on the right side. There were no effects of energy level or Ca-P levels on structural soundness scores (Barczewski et al., 1990).

Jørgensen and Sørensen (1998) examined the effects of different rearing intensities on leg weakness traits, culling for leg weakness, and culling for any reason.

Gilts ( $n = 72$ ) were fed at three levels between six weeks of age and mating. The three levels were semi *ad lib* (*ad libitum* feeding until 10 wk of age then *ad libitum* feeding for 30 min twice daily), control (feeding scale according to the Danish standard), and 75% control. After mating, all animals received the same feeding regimen. Leg weakness problems and long claws were scored on a 4-point scale at six months of age and in late pregnancy (between day 70 and 100) each parity from parities 1 to 4. The traits scored were buck-kneed and weak pasterns in the forelegs, steep hock joints, weak pasterns, and legs turned out in the rear legs, stiff in rear, swaying hindquarters, and lameness/sore-legged during locomotion, and long claws on both the front and rear legs. No individual trait was significantly impacted by rearing treatment, though weak pasterns in the hind legs and long claws in the front legs approached significance ( $P < 0.07$ ), with the semi *ad lib* treatment being most severe and 75% control least severe, with control not significantly different from either treatment. When the sum of the scores for all traits was calculated, there was a significant difference between treatments ( $P = 0.004$ ) in which the semi *ad lib* treatment was more severe than both the control and 75% control which did not differ. No significant interaction effects were present between rearing intensity and parity. The frequency of culling due to leg disorders did not differ between treatments in the first four parities, likely due to experimental procedures mandating sows to remain in production through at least four parities unless culling was necessary. However, culling reasons were recorded past parity 4, and when all parities were considered, rearing intensity did have a significant effect on culling due to leg disorders ( $P < 0.01$ ). Specifically, 48% of the sows in the semi *ad lib* group were culled for leg disorders while only 26 and 21% of the sows in the control and 75% control groups, respectively, were

culled for leg disorders. Contrasts revealed that sows were culled for leg disorders at a younger age in the semi *ad lib* group than sows in the control ( $P < 0.05$ ) and the 75% control ( $P < 0.01$ ) groups, while control and 75% control did not differ ( $P = 0.29$ ). When all reasons for culling were included in the analysis, the treatment effect was only approaching significance ( $P = 0.1$ ). However, the semi *ad lib* vs. 75% control contrast was still significant ( $P < 0.05$ ; Jørgensen and Sørensen, 1998).

Similar studies evaluating energy, Ca, and P levels on conformation traits and structural soundness have been performed on boars. Kornegay et al. (1983) studied effects of *ad lib* vs. 75% *ad lib* energy level feeding and 100% vs. 150% of the NRC (1979) Ca and P recommendations using an experimental procedure like that of Calabotta et al. (1982a). Toe size increased as boars grew, though the rate of growth decreased over time. There was a significant energy effect ( $P < 0.05$ ) for circumference of the forelimb at 220 d of age and circumference of the hind limb and length of the ulna and metacarpal at 150 d of age after weight correction; limit-fed boars were larger with the weight correction. Effect of energy level on incidence and severity of pad lesions was inconsistent, though limit-fed boars had a lower incidence of pad lesions in some cases. There were a few instances where pad lesions, and to a lesser extent, horn lesions had a lower incidence in boars fed at the 150% mineral level. Overall structural soundness scores were more favorable in boars fed *ad lib* than limit fed boars ( $P < 0.01$ ) after correction for body weight (Kornegay et al., 1983). Hacker et al. (1994) compared four feeding regimens in developing boars ( $n = 96$ ). At 28 d of age, boars were assigned to *ad libitum* or 85% *ad libitum* (restricted) feeding groups. At around 30 kg of bodyweight, boars were reassigned to a feeding regimen, such that some boars were fed *ad lib* from 28

d of age to 110 kg bodyweight, some were fed *ad lib* from 28 d of age to 30 kg of bodyweight and restricted from 30 to 110 kg of bodyweight, some were restricted from 28 d of age to 30 kg of bodyweight and fed *ad lib* from 30 to 110 kg of bodyweight, and some were restricted from 28 d of age to 110 kg of bodyweight. Individual vs. group housing was also evaluated from 30 to 110 kg of bodyweight. Feeding level did not have much effect on conformation traits and movement of boars. The group that was fed *ad lib* for the duration of the experiment from 28 d of age to 110 kg of bodyweight had more leg problems than other groups due to turned out legs and pastern angles (referred to as “sloping pasterns”) measured in both the front and rear legs. However, there was an interaction with housing type ( $P < 0.05$ ), and this effect was only significant for boars that were individually penned as it was likely caused by the combination of faster growth and lack of exercise (Hacker et al., 1994).

Wang et al. (2016) fed boars ( $n = 61$ ) at three different energy intake levels between 170 and 250 kg of bodyweight. This experiment was split into two periods; period 1 was from 170 to 200 kg of bodyweight, and period 2 was from 200 to 250 kg of bodyweight. All toes had a significantly larger horn length ( $P < 0.05$ ) in the high energy group compared to the low energy group at the end of the experiment. Toe length was also greater ( $P < 0.05$ ) in the high energy group compared to the low energy group for all toes except the front outer toe, and horn height in the front toes differed ( $P < 0.05$ ) between high and low energy groups. Toe growth rate was significantly greater ( $P < 0.05$ ) in the high compared to low energy level for all toe measurements and all toes, except the front outer toe for horn length, toe width, and horn height. There was no difference ( $P > 0.05$ ) between energy levels in average claw lesion score or percentage of claw lesions at

any time point, despite being numerically higher in the high energy level group at all time points after wk 0. Percentage of lameness was higher ( $P < 0.05$ ) for the high energy level compared to the low energy level at the last two time points (wk 27 and 29). Two boars in the high energy group were culled for lameness, whereas no boars were culled in the medium and low energy groups; however, this was not a statistically significant difference ( $P > 0.1$ ; Wang et al., 2016).

Jørgensen (1995) assessed the effects of different energy and protein levels on leg weakness in growing pigs. Both barrows and gilts ( $n = 150$  each) were used in this study, and the experimental diets were fed from 25 to 100 kg of bodyweight. The five experimental diets were low, standard, and high protein levels at the *ad libitum* energy level and *ad libitum* or Norwegian or Danish recommended energy levels (control) at the standard protein level. Pigs were scored for 14 leg weakness traits on a scale of 1 (normal) to 4 (severe) one week prior to slaughter. These traits were buck-kneed, weak pasterns, legs turned out, and claws uneven on the forelegs, standing under, steep hock joints, upright pasterns, legs turned out, and claws uneven on the hind legs, stiff in rear, swaying hindquarters, twisting hocks, and uncoordinated locomotion when observing the pig in motion. Energy level had an effect ( $P < 0.05$ ) on forelegs turned out, weak pasterns in the forelegs, and upright pasterns in the hind legs. There was also a tendency ( $P = 0.07$ ) for an energy effect on buck-kneed forelegs. The sum of all traits was highly significant ( $P < 0.01$ ). In all cases, the control energy level showed less severe leg weakness than the *ad lib* energy level. Protein level had an effect ( $P < 0.05$ ) on weak pasterns in the forelegs and stiff in rear locomotion. However, there was not a clear directional effect of either trait as the low protein level was favorable over the standard

protein level for weak pasterns and the high protein level was favorable over the standard protein level for stiff in rear, with the third protein level not differing from either of the other two levels in both cases (Jørgensen, 1995).

While they did not feed different experimental diets, Tarrés et al. (2006) found that ADG greater than 485 g/d between 167 d of age and first mating increased culling due to lameness ( $P < 0.05$ ) and for any reason ( $P < 0.01$ ). Backfat thickness at first farrowing greater than 19 mm ( $P < 0.05$ ) and loin depth at first farrowing less than 40 mm ( $P < 0.05$ ) also increased risk of culling due to lameness (Tarrés et al., 2006). Dietary manipulations can be employed to alter gilt growth and achieve these recommended targets for improved structural soundness and longevity.

Quinn et al. (2015a) compared three different feeding regimens typically used for developing gilts. These three regimens were DEV, a diet formulated specifically for developing gilts and fed in a restricted manner at 2.25 kg/d between 70 and 130 kg of body weight and then *ad lib* from 130 to 140 kg to mimic flushing, FIN, a typical finisher diet fed *ad lib* from 70 to 140 kg of body weight, and GES, the typical finisher diet fed *ad lib* from 70 to 100 kg of body weight and then a typical gestation diet limit-fed at 2.25 kg/d from 100-130 kg body weight and *ad lib* from 130-140 kg to mimic flushing. The gilt developer diet used in the DEV treatment had a high energy to lysine ratio (14 MJ of DE/kg; 0.75% lysine) and included increased levels of Ca and P as well as a dietary supplement including additional zinc, copper, and manganese. The typical finisher diet contained 13.5 MJ of DE/kg and 1.02% lysine while the typical gestation diet contained 13 MJ of DE/kg and 0.69% lysine. The DEV and GES feeding regimens met the NRC (2012) Ca and digestible P requirements for developing gilts, while the FIN diet did not.

Gilts ( $n = 36$ ) were blocked on weight and locomotion score and randomly assigned to a dietary regimen. Locomotion was scored on a scale of 0 to 5, and claw lesions and toe unevenness were scored on a scale of 0 to 3. Locomotion scoring occurred weekly, and claw lesion and toe unevenness scoring occurred when gilts weighed 70, 100, 130, and 140 kg on average. Locomotion score was reclassified as a binary trait of not lame (score  $\leq 1$ ) or lame (score  $\geq 2$ ). All gilts were slaughtered at 140 kg, which is the typical target weight for first service of replacement gilts. Areal bone mineral density and joint surface lesions were assessed post-slaughter. There were no differences in locomotion at 70 kg or between 70 and 100 kg ( $P = 1$ ). However, incidence of lameness increased over time after 100 kg for treatments FIN and GES ( $P < 0.05$ ). There were significant differences between treatments for locomotion between 100-130 kg ( $P = 0.02$ ), 130-140 kg ( $P = 0.01$ ), and across the entire study period ( $P < 0.001$ ). The percentage of animals classified as lame on at least one observation were 0, 73, and 75%, of animals on DEV, FIN, and GES regimens, respectively. No differences in claw lesions between treatments were observed; however, DEV gilts had a lower occurrence of uneven toes than FIN or GES at 140 kg of body weight ( $P < 0.001$ ). There was no correlation between locomotion score and claw lesion nor uneven toe scores. Feeding regimen had no effect on areal bone mineral density, and there was no correlation between areal bone mineral density and locomotion score. Gilts on the DEV dietary regimen had less severe joint surface lesions on the humeral condyle than gilts on FIN and GES ( $P = 0.051$ ) while no differences between treatments existed for the anconeal process. There tended to be a positive correlation between humeral condyle joint surface lesion score and locomotion score ( $P = 0.08$ ). There were no differences in body weight or carcass characteristics between

dietary regimens at slaughter; therefore, time at first breeding would not need to be shifted because of feed restriction and other developmental dietary changes evaluated in this study (Quinn et al., 2015a).

In three trials, Knauer et al. (2012) compared a finisher diet to a gestation diet both fed *ad lib*, *ad lib* and limit fed gestation diet, and two different feeding levels of a gestation diet. In each trial, dietary treatments began at approximately 114 kg of bodyweight. Muscle mass, rib width, front leg side view, rear leg side view, front legs front view, rear legs rear view, and locomotion were scored at approximately 136 kg. Muscle mass and rib width were scored on a 5-point scale, with 5 being more heavily muscled and wider through the center of the rib cage, respectively. The other traits were scored on a 7-point scale. For locomotion, a score of 1 was favorable while a score of 7 was severely lame. For front leg side view, rear leg side view, front leg front view, and rear leg rear view, a score of 4 was normal while a score of 1 indicated soft pasterns, sickle-hocked, splay-footed, and cow-hocked and a score of 7 indicated buck-kneed, post-legged, pigeon-toed, and legs turned in. No significant differences were observed in conformation traits or locomotion between diets in any trial ( $P > 0.05$ ). There was a trend ( $P = 0.08$ ) for the finisher diet to have softer pasterns than the gestation diet when both were fed *ad lib* (3.8 vs. 4.0 average front leg side view score). Muscle mass and rib width were also suggestively ( $P = 0.06$  and  $0.07$ , respectively) greater in the higher feeding level when a gestation diet was limit-fed at two different levels (muscle mass of 2.0 vs. 1.9 and rib width of 2.8 vs. 2.6; Knauer et al., 2012). The dietary treatments in these studies did not begin until later in life than those in Quinn et al. (2015a), which may be the primary reason differences between treatments were not observed.



Dietary factors during gilt development have been reported to influence conformation. However, specific effects vary between studies. Nearly all effects of reduced energy intake compared to *ad libitum* feeding on conformation were favorable, though adjusting for BW reduced or reversed some effects. Raising dietary Ca and P levels above NRC requirements had little impact on conformation compared to dietary Ca and P levels at NRC requirements. Increased dietary protein level provided some conformation benefits but was also detrimental to other aspects of conformation in growing pigs. Little research has been done to assess effects of dietary protein levels during gilt development on conformation of breeding females. Feeding a diet specifically formulated for developing gilts is advisable as improvements in conformation have been demonstrated in some instances, particularly when compared to finisher diets higher in energy and lower in minerals. As results are variable between studies and study periods often end early in life, further study is still needed to clarify the role of energy and protein intake during gilt development on lifetime conformational integrity.

## **1.6 Genetic Strategies for Improving Conformation**

### **1.6.1 Phenotyping**

Phenotypes are required for any genetic selection program. However, a standardized, objective phenotyping method has not been established for conformation traits. Many researchers have utilized subjective numerical scoring systems to assess lameness, locomotion, broadly defined conformation, or more specific conformation of a single limb, joint, body size or type trait, or foot lesion. Methods vary between studies with very few studies utilizing the same or even similar systems. For example, the different nomenclature and scales utilized to assess lameness are presented in tables 1.3

and 1.4. It is noteworthy that even when multiple studies use the same trait nomenclature, the method of scoring the trait is often different between them.

Table 1.3. Nomenclature of traits assessing lameness in the literature

<b>Trait Nomenclature</b>	<b>References</b>
<b>Lameness</b>	Heinonen et al., 2006; Schenck et al., 2008; Street and Gonyou, 2008; Elmore et al., 2010; Pluym et al., 2013b; Cador et al., 2014; Calderón Díaz and Boyle, 2014; Calderón Díaz et al., 2014; Knage-Rasmussen et al., 2014; Knox et al., 2014; Pluym et al., 2017; Fabà et al., 2018; Devillers et al., 2019; Pfeiffer et al., 2019
<b>Locomotion or Locomotory Ability</b>	Knauer et al., 2011; Knauer et al., 2012; Quinn et al., 2015a; Wang et al., 2016
<b>Motorics</b>	Aasmundstad et al., 2014b
<b>Gait Score</b>	Fukawa et al., 2001; Lee et al., 2003; Harris et al., 2006; Guo et al., 2009; Guo et al., 2013; Etterlin et al., 2015
<b>Movement</b>	Bereskin, 1979; Hacker et al., 1994; Andersen and Bøe, 1999; Le et al., 2015; Le et al., 2016
<b>Stiff in Rear, Swaying Hindquarters, and Stiff in Front or Sore-legged</b>	Jørgensen and Sorensen (1998); Jørgensen (2003)

Table 1.4. Scales used to subjectively assess lameness in the literature

<b>Assessment Scale</b>	<b>References</b>
<b>Binary</b>	Pluym et al., 2013b; Cador et al., 2014; Calderón Díaz and Boyle, 2014; Knage-Rasmussen et al., 2014; Knox et al., 2014; Wang et al., 2016; Pluym et al., 2017; Fabà et al., 2018; Pfeiffer et al., 2019
<b>3-point</b>	Andersen and Bøe, 1999; Fukawa et al., 2001; Lee et al., 2003; Heinonen et al., 2006; Le et al., 2015; Le et al., 2016
<b>4-point</b>	Street and Gonyou, 2008; Aasmundstad et al., 2014b; Etterlin et al., 2015
<b>5-point</b>	Bereskin, 1979; Schenck et al., 2008; Guo et al., 2009; Guo et al., 2013; Devillers et al., 2019
<b>6-point</b>	Harris et al., 2006; Elmore et al., 2010; Calderón Díaz et al., 2014; Quinn et al., 2015a
<b>7-point</b>	Knauer et al., 2011; Knauer et al., 2012; Le et al., 2015
<b>8-point</b>	Hacker et al., 1994

There are many specific traits that can be classified as “conformation”, each with potentially different effects on sow longevity, productivity, and welfare. Studies of swine conformation vary greatly in specificity of the conformation traits assessed. Broad definitions of conformation included overall type (López-Serrano et al., 2000), overall score (Le et al., 2015; Le et al., 2016), overall conformation (Le et al., 2017) leg soundness (Serenius and Stalder, 2007), leg weakness (Huang et al., 1995), leg status (López-Serrano et al., 2000), and overall leg action (Serenius et al., 2001; Serenius et al., 2004; Serenius and Stalder, 2004; Fan et al., 2009; Fan et al., 2011; Nikkilä et al., 2013a, b). Sobczyńska et al. (2013) used an even broader trait called exterior index, which included overall type, leg status, number and quality of teats, muscle, and body length. Fredeen and Sather (1978), Fukawa et al. (2001), Tiranti and Morrison (2006), Guo et al. (2009), Guo et al. (2013), Aasmundstad et al. (2014b), and Le et al. (2017) assigned a score to forelimbs and hind limbs. Bereskin (1979) scored toes and front and rear feet and legs. While more specific than an overall conformation score, they considered multiple aspects of all toes and conformation of multiple joints in both legs. Similar traits were utilized in Le et al. (2015), called front leg quality, rear leg quality, and toes quality. Lee et al. (2003), Uemoto et al. (2010), Laenoi et al. (2011), and Laenoi et al. (2012) assigned scores to front and rear legs and front and rear feet.

To evaluate distinct joints or aspects of body shape and size, more specific trait definitions are necessary. Traits assessing a specific aspect of conformation in swine are summarized in table 1.5. Despite the necessity of evaluating many traits, standardization of assessment methods of the traits is imperative. The same specific aspect of conformation has been evaluated in different ways. For example, pastern angles have

Table 1.5. Specific conformation traits evaluated in the literature

<b>Trait Type</b>	<b>Specific Trait Names</b>
<b>Body Size</b>	Body length, height, body depth, body width, rib width, cannon circumference <sup>1</sup>
<b>Body Type</b>	Rib shape, top line/back quality, hip structure, muscle/muscle mass <sup>2</sup>
<b>Leg Conformation</b>	Weak pastern/plantigradism/down at pasterns, straight pastern/upright pastern/up on toes, pastern posture, buck knees/over at the knees, knock knees, bow legs, sickle-hooked leg, standing under position, close hocks, hock angle, steep hock joints, leg posture, upright/weak legs, front leg side view, rear leg side view, front legs front view, and rear legs rear view <sup>3</sup>
<b>Foot Traits</b>	Claw score, overgrown hooves/excessive or abnormal hoof/toe growth, claw/toe growth, foot size, hoof/toe/claw length, small inner claws, accessory digit or dew claw length/dew claw growth and integrity, dew claw injuries, unequal claw size/uneven toes/asymmetry between toes/length difference between toes/disparity hooves, splayed feet <sup>4</sup>
<b>Foot Lesions</b>	Cracked hooves, wall cracks, horizontal wall cracks, vertical wall cracks, wall separation, wall penetration, wall bruising, wall haemorrhage, wall lesions, wall and toe lesions, coronary band lesion, toe lesion, toe erosion, sole erosion, heel erosion, heel-sole erosion, heel overgrowth and erosion/cracks, heel flaps, heel corrugation, heel haemorrhage, heel lesions, heel-sole bruising, heel-sole crack/lesion, sole haemorrhage, sole lesion, white line cracks/damage, white line lesion, false sand cracks, toe pad condition, average foot pad score, hoof lesions and bruising <sup>5</sup>

<sup>1</sup>López-Serrano et al., 2000; Fukawa et al., 2001; Fan et al., 2009; Fan et al., 2011; Knauer et al., 2011; Knauer et al., 2012; Nikkilä et al., 2013a, b

<sup>2</sup>López-Serrano et al., 2000; Fan et al., 2009; Fan et al., 2011; Knauer et al., 2011; Knauer et al., 2012; Nikkilä et al., 2013a, b; Le et al., 2017

<sup>3</sup>Hacker et al., 1994; Jørgensen and Sorensen, 1998; Serenius et al., 2001; Jørgensen, 2003; Serenius et al., 2004; Fernández de Sevilla et al., 2008, 2009a, b; Fan et al., 2009; Fan et al., 2011; Knauer et al., 2011; Knauer et al., 2012; Nikkilä et al., 2013a, b; Aasmundstad et al., 2014b; Le et al., 2015; Pfeiffer et al., 2019

<sup>4</sup>Hacker et al., 1994; Jørgensen and Sorensen, 1998; Mouttrotou et al., 1999; Fukawa et al., 2001; Serenius et al., 2001; Knauer et al., 2007; Fan et al., 2009; Fernández de Sevilla et al., 2008, 2009 a, b; Gillman et al., 2009; Fan et al., 2011; Pluym et al., 2011; Fitzgerald et al., 2012; Calderón Díaz et al., 2013; Nikkilä et al., 2013a, b; Pluym et al., 2013b; Cador et al., 2014; Calderón Díaz et al., 2014; Knage-Rasmussen et al., 2014; Lisgara et al., 2015; Quinn et al., 2015b; Lisgara et al., 2016; Wang et al., 2016; Fabà et al., 2018; Wang et al., 2018; Pfeiffer et al., 2019

<sup>5</sup>Newton et al., 1980; Brennan and Aherne, 1987; Mouttrotou et al., 1999; Knauer et al., 2007; Schenck et al., 2008; Gillman et al., 2009; Pluym et al., 2011; Fitzgerald et al., 2012; Calderón Díaz et al., 2013; Pluym et al., 2013b; Cador et al., 2014; Calderón Díaz et al., 2014; Lisgara et al., 2015; Sasaki et al., 2015; Lisgara et al., 2016; Olsson et al., 2016; Varagka et al., 2016; Wang et al., 2016; Fabà et al., 2018; Falke et al., 2018; Wang et al., 2018

been evaluated as “pastern posture” (Fan et al., 2009; Fan et al., 2011; Nikkilä et al., 2013a, b; Pfeiffer et al., 2019), “weak pastern/plantigradism/down at pasterns” (Hacker et al., 1994; Jørgensen and Sørensen, 1998; Fernández de Sevilla et al., 2008, 2009a, b) and “straight pastern/upright pastern/up on toes” (Hacker et al., 1994; Serenius et al., 2001; Jørgensen, 2003; Fernández de Sevilla et al., 2008, 2009a, b) to focus on extremes, or included in more general traits of “leg posture” (Nikkilä et al., 2013a, b) and “upright legs”/“weak legs” (Fan et al., 2009; Fan et al., 2011). Like lameness, as illustrated above, subjective scales used to score traits vary widely between studies, ranging from binary to 9-point. A scale from 0 to 100 was even used to score broadly defined conformation (Sobczyńska et al., 2013). Within the same study, different scales may be used for distinct traits (Bereskin, 1979; Serenius et al., 2001; Fernández de Sevilla et al., 2008, 2009a, b; Knauer et al., 2011; Laenoi et al., 2011; Knauer et al., 2012; Laenoi et al., 2012; Aasmundstad et al., 2014b; Le et al., 2015; Le et al., 2017; Pfeiffer et al., 2019). Furthermore, many conformation traits are complicated by intermediate optimums and low numbers of animals in certain categories. These problems may be mitigated by redistribution of the scale as in Serenius and Stalder (2007) and Nikkilä et al. (2013a).

Main et al. (2000) developed a subjective lameness scoring system and assessed repeatability between observers. The scoring system is on a scale of 0 to 5, and considers five attributes of pig posture, gait, and behavior: initial response to human presence, pig’s response after opening gate, behavior of individual within the group, standing posture, and gait. Each level had defining criteria required for a specific score to be assigned, while other attributes were considered useful supporting evidence. A score of 0 required gait to be even strides with no abnormalities present. A score of 1 required abnormal

stride length and movements that are no longer fluent, with no abnormalities present in other categories. A score of 2 was defined by uneven posture, while a score of 3 required uneven posture and reluctance to bear weight on the affected limb. A score of 4 required that the pig be unwilling to leave a familiar environment, hold the affected limb elevated off the floor when standing, and not place it on the floor while moving. Pigs that are dull and unresponsive when approached by a human and cannot walk are given a score of 5. The kappa statistic was used to measure the agreement of scores between observers; a kappa score of 0 indicates no agreement beyond chance, 1 indicates perfect agreement, and 0.4-0.5 demonstrates moderate agreement. Two observers familiar with the scoring system independently evaluated the lameness of 201 growing and finishing pigs (weight range 40 to 100 kg). They assigned the same score to 94% of the pigs, the kappa statistic was high (0.9), and a P-value of  $< 0.001$  indicated significant agreement beyond chance. Seven untrained and unfamiliar observers were also given a copy of the scoring system and asked to score 19 of the pigs scored by the two trained, familiar observers on the same day. Agreement between unfamiliar and trained observers was low; the percentage of agreement and kappa statistic ranged from 26 to 53% and -0.01 to 0.35, respectively. While four of the seven unfamiliar observers had agreement with trained observers greater than expected by chance ( $P < 0.05$ ), and 88% of the scores given by unfamiliar observers were within one score of those given by familiar observers, the low agreement percentage and kappa statistic indicate that this scoring system is not repeatable unless observers are trained and familiar with the system. Proper initial training and frequent retraining are required for this subjective scoring system to be reliable (Main et al., 2000). D'Eath (2012) used a simplified version of the scoring system developed by Main

et al. (2000) to assess lameness in sows and inter-observer reliability of scoring. The sows used in the study ranged from maiden gilts to parity 7 sows and were in all dry phases of production, from just weaned to heavily pregnant, on one farm. Scoring was performed 11 times total over a period of 566 days; between 47 and 76 sows were available to be scored at each event (not in the farrowing house). The scoring system still used categories of 0 to 5, but mainly focused on the defining criteria mostly within the gait and posture attributes, though reluctance to get up and unresponsiveness to human approach were considered for the latter categories. Sows were encouraged to walk for scores to be assigned, and each observer was instructed to watch a sow complete at least ten strides before assigning a score. The observers ( $n = 5$ ) all had experience working with pigs but no previous experience or formal training with this scoring system, though it was explained and discussed prior to beginning scoring. Two observers attended all 11 scoring events, while two observers were present for nine events, and one was present for four events. Inter-observer reliability was considered in three ways. First, whether observers differed systematically in the absolute level of scores assigned was assessed using a Friedman test to compare all observers for the same sow on the same occasion and Wilcoxon tests to compare pairs of observers. There was a highly significant difference between all observers ( $P < 0.001$ ). Second, whether scores from different observers were an exact match or proportion of agreement were assessed using kappa and PABAK (kappa adjusted for prevalence and bias) statistics (D'Eath, 2012). Similar to Main et al. (2000), kappa and PABAK were interpreted as 0 or less being no agreement, 0.01 to 0.2 poor agreement, 0.21-0.4 slight agreement, 0.41-0.6 fair agreement, 0.61-0.8 good agreement, 0.81-0.9 very good agreement, and 0.91-1 excellent agreement (D'Eath,

2012). Kappa and PABAK were calculated for overall and between pairs of observers and for individual assigned scores. Overall kappa was 0.443, while overall PABAK was 0.692. Adjusting for prevalence and bias raised the agreement from “fair” to “good” because lower scores had a much greater prevalence and bias between observers was shown to exist. Kappa values between observers ranged from 0.249 and 0.679. When comparing individual assigned scores, Kappa and PABAK were lower for score 1 than other scores, likely because the threshold between 0 and 1 is difficult to pinpoint and agree upon. When converted to a binary system, with scores of 0 to 1 and 2 to 5 combined, overall kappa was 0.653, while kappa between pairs of scorers ranged from 0.478 to 0.852, suggesting that a simpler system has better reliability. Finally, association between scores from different observers was assessed with Kendall’s coefficient of concordance and Spearman’s and Kendall’s rank correlations. The overall Kendall’s coefficient of concordance was 0.692, while Spearman’s and Kendall’s rank correlations between pairs of observers were similar to each other and ranged from 0.457 to 0.781. Reliability at individual time points ranged from 0.552 to 0.879. Reliability improved over time and reached a plateau around the fourth or fifth scoring event. Practice likely improved intra-observer reliability, though this was not measured in this study, and discussions between observers about the scoring process and how to handle borderline cases likely put them more on the same page over time. Training and regular assessment of inter-observer reliability is important to achieve reliable, standardized data collection (D’Eath, 2012). Van Steenberg (1989) also assessed inter- and intra-observer reliability using an exterior trait scoring system with a scale of 0 to 9 with increments of 0.5, allowing for 19 total categories. Forty boards were scored using this system by ten



observers, each scoring them twice. Most observers preferred whole number categories, and there were differences in mean and standard deviation between observers. Average repeatability, between the two scores assigned by the same person, was 0.6 while average reproducibility, between scores assigned by different people, was 0.3. These results, while deemed satisfactory in 1989, also highlight the importance of observer training (Van Steenberg, 1989).

While subjective scores have been the norm for conformation assessment, some studies have used more objective measurements. A ruler was used to get measurements for toe length, sole length, and sole width in mm in Newton et al. (1980). Newton et al. (1980) also counted number of cracks in the hoof on each toe and number of other lesions on the feet rather than just assigning an approximate score. Sasaki et al. (2015) also measured toe length, claw height, claw width, sole length, and dew claw length. In Marchant and Broom (1996), sows were measured for body length, height at shoulder, and width across shoulders, while Fukawa et al. (2001) measured body length, withers height, chest girth, and cannon circumference on gilts, boars, and barrows. A caliper was used by Calabotta et al. (1982a), Arthur et al. (1983), Kornegay et al. (1983), and Wang et al. (2016) to measure toe size, including toe width and length and horn length and height. van Amstel and Doherty (2010) also used a caliper to measure toe size traits in a pilot study looking at toe growth compared to toe wear.

Calabotta et al. (1982b) and Barczewski et al. (1990) used cameras to photograph sows walking at a rate of several frames per second. These images were projected onto a reverse projection screen, where objective body size and angle measurements could be taken. Body size measurements from the side view were torso length, distance from

shoulder to arc point of the back, height of back arc, girth diameter (or body depth) at the back arc, and pig height at the back arc. Leg angles from the side view were front and rear pastern angles, hock angle, knee angle at the point of maximum flex as the front leg is lifted in motion. Front and rear foot height when the foot is off the ground during the walking cycle was also measured from side view images. Width at the widest point across the hams, distance of lateral tail movement, distance between the hocks, and deviation of the hock from the edge of the hams on both the left and right side as a measure of leg curvature were measured from the rear view. Stock et al. (2017) took digital photographic images as sows ( $n = 24$ ; parity 5 and greater) were standing from the right and left side and the rear. Knee, hock, both front and rear pastern, and rear stance angles were manually and objectively measured using ImageJ. A minimum of four images were captured at a single time from each location on each individual sow. Angle measurements were taken from both the anterior and posterior side of the knee, hock, and pastern joints. Intraclass correlations were calculated between the measurements from the multiple images of each individual for all angle measurements. For angles that had both anterior and posterior measurements, intraclass correlations were calculated for the average of the anterior and posterior measurements and the anterior measurements only for comparison. Intraclass correlations ranged from 0.49 (knee angle mean joint measurement) to 0.83 (hock angle mean joint measurement). Aside from the knee, which had an increased correlation of 0.66 when only the anterior measurement was used, intraclass correlations were very similar between the mean of both anterior and posterior measurements and the anterior measurement only. Therefore, it is recommended to only use the anterior measurement as knee angle intraclass correlation is improved by using

only the anterior measurement, and only taking one measurement instead of two for each joint is less labor-intensive. With only the anterior measurements (and the mean of each leg for rear leg stance as this measurement did not have anterior and posterior angles), intraclass correlations ranged from 0.63 (front pastern angle) to 0.82 (hock angle) between different images taken of the same sow, indicating that they are repeatable (Stock et al., 2017).

Stavarakakis et al. (2014) used quantitative measures of gait kinematics to see if joint and stride kinematic differences existed in sound vs. unsound pigs and pigs with or without osteochondrosis joint lesions. Both male ( $n = 12$ ) and female ( $n = 12$ ) growing pigs (starting weight = 63 kg) were filmed with infrared cameras set up along a walkway to capture three or four acceptable strides, steady and regular movement with no disruptions, in each direction. Reflective markers of adhesive tape were placed on 34 anatomical locations on each pig to track movement using a custom-written program in Matlab. The program was able to detect stride events, create angle curves normalized for stride time, calculate joint angles, and define minimum and maximum values as well as the range of motion during the stance and swing phases. Subjective scores were assigned weekly for lameness and conformational deficiencies of buck knees, sickle hocks, post legs, splay feet, pigeon toes, weak pastern, upright pastern, uneven claws, leg shape, hump back, and broken back. Joint lesions caused by osteochondrosis were scored on the major articulations of all legs after slaughter at 90 kg. Lameness was scored on a 6-point scale, conformational deficiencies were scored on a 4-point scale, and joint lesions were scored on a 5-point scale. Lameness and/or pigs with conformational deficiencies had gait changes related to the swing phase of the stride, particularly in the range of motion at

the joints and symmetry between left and right joint flexion. However, buck knees specifically resulted in decreased flexion in the stance phase ( $P \leq 0.05$ ; -9 degrees). The stance phase of the stride was primarily affected by joint lesions, which caused angular differences ( $P \leq 0.05$ ) and asymmetry during this phase. Since joint lesions and clinical appearance of lameness had greater effects on different parts of the stride and had a low to moderate intra-class correlation coefficient (0.221;  $P = 0.144$ ), subjective scores of lameness and conformation may not be good indicators of joint lesions. The step to stride length ratio had greater irregularity in pigs classified as subclinical ( $P = 0.06$ ) and clinical ( $P \leq 0.05$ ) compared to pigs classified as healthy based primarily on lameness and conformational deficiencies scores. The range of motion of the knee joint during the swing phase tended to be smaller in pigs with buck knees, but greater in pigs with hind leg deficiencies. In some cases, front leg deficiencies resulted in greater asymmetry in the hind legs while hind leg deficiencies resulted in greater asymmetry in the front legs. Compensation on the unaffected limbs could be more visible by kinematic analysis than the effects on the affected limb (Stavarakakis et al., 2014). Kinematic analysis was also used by Devillers et al. (2019) to assess how different gap and slot widths affect the gait of gilts (with smaller feet) and lame sows using a similar protocol to Stavarakakis et al., (2014). Sows had nine reflective markers in specific anatomical locations and were filmed walking, but from one side only. MoviAS pro software was used to measure walking speed, stride length, swing time, stance time, foot height, and angle mean and amplitude for the carpal and tarsal joints during the swing and stance phases (Devillers et al., 2019). Tinkle et al. (2017) also used kinematic analysis to study the effects of functional claw trimming on gait in sows. Kinematics were assessed using video

recordings, and the Kinovea program was used to identify stance duration, swing duration, breakover time, stride length, total stride duration, swing:stance ratio, breakover as a percentage of stride duration, stance as a percentage of stride duration, and percentage of 3-limb support (Tinkle et al., 2017).

Measuring weight distribution or the amount of weight supported by each limb is another potential objective method of lameness detection, as sows will likely place less of their weight on a lame or structurally compromised limb (Sun et al., 2011). For this purpose, a force plate was designed that contains four quadrants, each with its own load cell to capture the vertical forces produced by each leg of the sow separately (Sun et al., 2011). It was embedded with a microcomputer system that could transfer the data collected to a laptop computer. This system was calibrated and validated first by using certified weights, then by testing it on eight sows, four of which were visually lame in at least one hoof. Approximately 1800 weight measurements were taken on each sow as they stood on the force plate for 30 minutes. Each sow placed more weight on their front legs rather than hind legs regardless of lameness status; average percentage of weight placed on front and hind legs were 56.5% and 43.5%, respectively. However, across the 30 min measurement period, variation between front vs. hind weight distributions could be quite large. While rare, there were measurements in which > 95% of the weight was on either the front or rear legs. On the contrary, left vs. right weight distribution was sow-dependent as two sows averaged more weight on their left side while six averaged more weight on their right side. Graphs of each individual weight measurement were difficult to interpret due to large fluctuations, but when 60 s rolling averages were used, graphs clearly demonstrated even weight distribution patterns for non-lame sows and lower

weight bearing on one leg in sows that were visually lame, providing a proof of the concept (Sun et al., 2011). A follow-up study was performed to determine the amount of time required to collect accurate data on the force plate (McNeil et al., 2018). Sows ( $n = 12$ ) were induced to be lame using amphotericin B in either their left or right rear foot and put on the force plate for measurement of weight distribution the day prior to lameness induction and one, six, and ten days after lameness induction. This experiment was repeated three times, with sows given plenty of time to recover between lameness inductions. Weight bearing data were collected two times per second for 15 minutes per sow at each time point, and inaccurate outlying data points were removed. Average force, percentage of total force, standard deviation of applied force, skewness, 5<sup>th</sup> and 95<sup>th</sup> percentile of force applied, and the range between the 95<sup>th</sup> and 5<sup>th</sup> percentile were calculated for each sow on each quadrant on each day. This study was able to observe a decrease in weight placed on the leg induced to be lame after lameness induction that slowly resolved over time. The data became more variable after 12 minutes than in the previous 11 minutes; therefore, using data recorded after 10 minutes is not recommended. The variables calculated using data from one, five, and ten minutes did not significantly differ. Furthermore, including burn-in times of 15, 30, and 45 seconds also did not affect the variables calculated, and there were still no differences when using data from one, five, or ten minutes with any of the burn-in periods ( $P > 0.05$ ). Therefore, measurements collected for one minute with no burn-in period is sufficient for accurate weight distribution data when using this force plate system (McNeil et al., 2018).

A similar force plate system called SowSIS (sow stance information system) was developed by Pluym et al. (2013a). This system has a similar appearance to a regular

scale, but the bottom platform contains four balances to measure legs individually. This system also contains a rotatable arm with a digital camera and sides that can be raised and lowered to take pictures of specific joints or other anatomical features. Data were collected as sows stood on the force plate for at least five minutes to obtain a total of 3000 data points that were subsequently cleaned to remove inaccurate outliers. Variables calculated from force plate data include the weight exerted by each leg, weight exerted by a leg relative to other legs, relative weight of left vs. right legs, kicks, weight shifts, and leg weight symmetry of the left and right sides. Angles of the claw, pastern, and hock were calculated from pictures taken by the camera. Repeatability of variables was assessed by measuring sows ( $n = 20$ ) five times within an hour. Prior to measurement, all sows were visually scored for lameness, and only one was found to be lame. As was the case in Sun et al. (2011), Pluym et al. (2013a) also found that sows bear more weight on their front legs (58%) compared to their hind legs (42%). More kicks were observed on the hind legs, while more weight shifts occurred in the front legs. Kick duration was greater in the hind legs, and weight shift duration did not differ between legs. Within animal coefficients of variation were low ( $< 10\%$ ) for weight exerted by each leg, weight exerted by a leg relative to other legs, relative weight of left vs. right legs, leg weight symmetry of the left and right sides, and claw and hock angles. Pastern angle and magnitude of weight shifts had moderate within-animal coefficients of variation (11.6-17.8%). Number and duration of kicks and weight shifts had higher within-animal coefficients of variation ranging from 23.6% (number of weight shifts between the left and right front legs) and 151.3% (duration of right hind leg kicks). Consecutive measurements on the same sow were not significantly different for any variable ( $P >$

0.05), except for number of weight shifts between left front and left hind leg ( $P = 0.043$ ), duration of weight shift between left front and left hind leg ( $P = 0.009$ ) and between right front and right hind leg ( $P = 0.004$ ), and magnitude of weight shifts between the left front and left hind leg ( $P = 0.007$ ). A preliminary case-control study comparing four sound sows with four sows that were lame on their right rear leg demonstrated the ability of this system to detect differences between the sound and lame sows. Differences ( $P < 0.05$ ) between sound and lame sows were obtained for several parameters involving average and maximum weight exerted, coefficient of variation of weight exerted, minimum and maximum relative weight, number of leg kicks, number and duration of weight shifts, and leg weight symmetry. The differences in these parameters were present for some, but not all limbs (Pluym et al., 2013a).

Accelerometers have also been evaluated as a method of objective and automated lameness detection. Traulsen et al. (2016) utilized ear sensors to collect sow positioning and acceleration data of 212 sows ranging from parities 2 to 5 in a group-housed system. The collection period was about a year long, and data was collected during gestation from 296 total parities (84 sows with 2 parities). Ear sensors were sampled every second by 12 receivers placed at different positions throughout the pen. Positioning data was used to calculate the path length walked by a sow during a day and the number of squares visited by a sow in a day. The pen was divided into 25 x 25 cm squares for this measurement. Average acceleration at the sow's ear per day was also calculated. Lameness events were diagnosed in two ways; farm staff checked sows once a day and recorded incidences of lameness, and all sows were assigned a lameness score once a week on a scale of 0 to 2. The lameness period was defined as the 14 days leading up to the lameness diagnosis by



either farmer observation or a lameness score of 2 (clearly visible lameness). Path length, number of squares, and acceleration data was compared between this 14-day lameness period and the 14 days prior to the start of the lameness period. Overall, sow activity decreased as gestation day increased. In lameness events identified by farmer observation, the path length and number of squares were lowest on the day of lameness diagnosis and decreased in the days leading up to it. Path length did not differ between the day of diagnosis and the three days prior ( $P > 0.05$ ). However, the path length traveled most days before the three days leading up to lameness diagnosis was significantly greater ( $P < 0.05$ ) than the day of diagnosis. All days leading up to lameness diagnosis were significantly greater ( $P < 0.05$ ) than the day of diagnosis for number of squares. No clear pattern in acceleration could be found. In lameness events identified by lameness scoring, a decrease in path length and number of squares leading up to the lameness diagnosis was present; however, it was of a much smaller magnitude, and only the first two days of the non-lame period (28 and 27 days prior to lameness diagnosis) were significantly different ( $P < 0.05$ ) from the day of lameness diagnosis. Acceleration did not produce a clear pattern in sows detected as lame through scoring either. Linear models that estimated average values for each day were used in this study. However, repeatabilities were around 45%, which indicate that sows have individual activity patterns that should be considered (Traulsen et al., 2016). Analysis that compared activity around a lameness event to a baseline specifically determined for each sow may have been able to identify clearer decreases in activity.

Kongsro et al. (2013) developed a vision system to evaluate pig structural soundness and locomotion using multivariate image analysis. This system utilized a web

camera that was mounted to the ceiling and connected to a PC. Boars ( $n = 288$ ) were individually herded between pens to pass under the web cam. Frame grabbed images were stored from parts of the video where motion was detected using motion detection software. Analysis was performed in MATLAB using the Image Processing Toolbox and the Statistics Toolbox. To process images, they were first imported from the grabbed frames, cropped, and converted to grayscale. The pig was segmented from the background to obtain a binary image of the pig. Background noise was filtered out, and further filtering was performed to only capture images where the pig was moving in a left to right direction as this was the direction they were walked between pens. Interference from background, tail, or feet was removed, and the pigs were rotated to a horizontal position and centered. Processed binary images were stacked on top of each other to map differences between pictures. A minimum of 15 images were used. Principal component analysis was performed on centered and centered and scaled data sets. Four principal components (PC) were identified. For data that was centered but not scaled, PC1 represented general movement and explained 71.7% of the total variation, PC2 represented diagonal movement between the hind and side parts of the pig and explained 7.54% of the total variation, PC3 represented minor motion patterns around the center of the body and explained 3.67% of the variation, and PC4 represented diagonal movement in the opposite direction of PC2 and explained 2.87% of the total variation. Scaling removed the general movement PC and likely overinflated others. This system does produce information, but a lot of improvements and further work are needed to make it meaningful. Out of 1700 boars, only 288 moved through the test area in a satisfactory way without stopping or turning around. A walkway or other site is necessary to

consistently achieve a standardized motion pattern from each pig. More work is needed to relate the PC to desirable vs. undesirable patterns of motion, and an automatic method of animal identification, such as electronic tagging or vision system identification, is needed (Kongsro, 2013).

Grégoire et al. (2013) compared several methods of phenotyping traits associated with lameness, including footprint analysis, kinematics, accelerometer data capturing posture and stepping behavior, foot lesion scores, and lying-to-standing transition scores. Sows of various parities and stages of gestation ( $n = 50$ ) were visually scored for lameness on a subjective scale and categorized as non-lame, mildly lame, and lame. All other phenotypes were compared to these lameness scores to identify if differences between lameness categories existed. All novel methods went through validation procedures prior to comparison with other phenotypes. Footprint analysis was accomplished via sows walking across a floor covered with clay. Footprints were identified on the clay, photographed with a digital camera, and analyzed with image analysis software to calculate stride length, contralateral distance, ipsilateral distance, and diagonal distance. Validation steps for this procedure first consisted of polygons drawn on the clay to simulate footprints and repeated walks from the same sows three times per day on two different days. Coefficients of variation were 1.16% (linear length) to 3.07% (angles) for the polygons, 3.47% (diagonal from rear limbs) to 11.82% (diagonal from front limbs) for walks by the same sow within the same day, and 4.65% (diagonal from rear limbs) to 11.11% (diagonal from front limbs) for walks by the same sow between days. None of the phenotypes obtained with this method were associated with sow lameness status ( $P > 0.5$ ). For kinematic analysis, reflective markers were placed at 11

locations on each side of the sows. Sows were video recorded while walking, and an automatic tracking program was used to determine walking speed, stride length, swing time, stance time, foot height, and mean carpal and tarsal joint angles and amplitudes. To validate this method, videos and measurements were taken from both sides of the sow, and the same sows were filmed and measured three times per day on two different days. Coefficients of variation ranged between 1.19% (mean rear limb tarsal angle) and 17.14% (front limb height) for walks by the same sow within the same day and 2.8% (mean rear limb tarsal angle) and 20.01% (rear limb height) for walks by the same sow on different days. Walking speed, stride length, and stance time were associated with lameness status ( $P < 0.05$ ). Non-lame sows walked faster than lame sows ( $P < 0.05$ ), while mildly lame sows walked at an intermediate pace that was not different from either non-lame or lame sows ( $P > 0.05$ ). Stride length was greatest in mildly lame sows and least in lame sows ( $P < 0.05$ ), with non-lame sows intermediate and not different from either mildly lame or lame sows ( $P > 0.05$ ). Stance time was increased in lame sows compared to non-lame and mildly lame sows ( $P < 0.05$ ). Stride length measured with the footprint analysis were shorter than those obtained via kinematics. The clay used for footprint analysis was slightly wet and slippery, likely causing sows to shorten their stride length to compensate. This is likely the reason for the difference between footprint analysis and kinematic measurements and the lack of association between footprint analysis and lameness status, and improved methodology for footprint analysis is needed. An accelerometer was attached to a rear leg to record sow posture every five s for 24 hr, and two accelerometers were attached to both rear legs to record leg position ten times/s in the hour following feeding to obtain percentage of time standing in the 24 hr period, steps/min in the hr after

feeding, and latency to lie down after feeding. Lameness category was significantly associated with time standing over 24 hr ( $P = 0.003$ ) and latency to lie down after feeding ( $P = 0.026$ ) and suggestively associated with stepping in the hr after feeding ( $P = 0.062$ ). Lame sows spent less time standing in the 24 hr period than non-lame and mildly lame sows ( $P < 0.05$ ). Lame sows also took more steps and lay down quicker following feeding than non-lame sows ( $P < 0.05$ ), with mildly lame sows intermediate and not significantly different from lame or non-lame sows ( $P > 0.05$ ). Foot lesions, which consisted of heel lesions and overgrowth, sole lesions, heel-sole junction lesions, white line lesions, side wall lesions, dew claw lesions, and claw size, were scored using a visual subjective scoring system on a 3-point scale on each claw of each foot. The 3-point scale was transformed into binary variables of presence vs. absence of any lesion and presence vs. absence of severe lesion. For validation, feet from five sows were evaluated repeatedly by two observers, and inter- and intra-observer reliabilities were 76% and 83%, respectively. There were significant effects of front vs. rear foot ( $P < 0.05$ ) on all lesions except white line and medial vs. lateral claw ( $P < 0.05$ ) on side wall, white line, sole, and dew claw lesions. No lesion type or total lesion score influenced lameness category ( $P > 0.05$ ). However, some foot lesions did have significant effects on gait measurements obtained via kinematics and footprint analysis. Specifically, presence of severe heel lesions reduced swing time in the front feet ( $P < 0.05$ ), presence of severe sole lesions reduced diagonal distance from front feet ( $P < 0.05$ ), and presence of severe white line lesions decreased sow walking speed ( $P < 0.05$ ), ipsilateral distance from front feet ( $P < 0.05$ ), and diagonal distance from front feet ( $P < 0.05$ ). Finally, lying to standing transition was subjectively scored using a 4-point scale as a sow was encouraged to stand.

While the scores obtained were very reliable, with inter- and intra-observer reliabilities both at 96%, many sows refused to stand despite the encouragement, and no differences were observed between lameness categories. It cannot be determined whether refusal to stand is due to locomotion problems or stubborn animals, and differences in human reactivity may also play a role, making this method less useful in assessing sow lameness. However, kinematics and accelerometers do appear to be useful for assessing lameness in sows (Grégoire et al., 2013).

Abell et al. (2014) compared the ability of objective weight distribution and gait measures and subjective visual lameness scores to detect induced lameness in sows. Multiparous sows ( $n = 24$ ; parities 1 to 4) were injected with amphotericin B near the toes on a randomly assigned foot to induce synovial membrane inflammation and cause lameness. The experiment was repeated with the second injection occurring in the leg lateral to the leg injected in the first replicate. Weight distribution was measured using a force plate, which measured the amount of weight placed on each leg two times per second for 15 min the day prior to lameness induction and each day for nine days after induction. The measurements obtained by the force plate were mean weight placed on each foot, the interquartile range, the 5<sup>th</sup> percentile of weight measurements, the 95<sup>th</sup> percentile of weight measurements, the standard deviation, the mode, and skewness and kurtosis of the weight distribution. Sows were walked across a GaitFour walkway system three times per day the day before induction and days one and six post-induction. The gait measurements obtained were stride length, stance time, stride time, maximum pressure placed on a foot per step, and number of sensors activated by steps on each foot. Sows were also visually scored for lameness by at least two scorers the day before

induction and days one to nine following induction. Classification tree analysis was performed, where the distribution for each variable is compared between lame and sound limbs. Variables that explain the largest proportion of variation between classifications are identified by having non-overlapping distributions. A random forest analysis was also used, which develops multiple classification trees and selects the most informative variables by determining the proportion of trees each variable is included in. The classification trees were cross-validated to determine predictive ability by removing all observations one-by-one from the analysis and using the remaining observations to predict its classification. Error rates were calculated as the percentage of incorrect classifications in this process. Differences from baseline (day prior to lameness induction) were considered detection of lameness for all methods. The visual scoring system detected lameness from days one to six post induction ( $P < 0.05$ ), but not days seven to nine ( $P > 0.05$ ). Likewise, most measures obtained using the force plate except for skewness of the weight distribution, detected rear foot lameness up to day seven post-induction ( $P < 0.05$ ) and front foot lameness up to day four post-induction ( $P < 0.05$ ). Gait measurements identified lameness on both front and rear feet at day one post-induction ( $P < 0.05$ ), but not day 6 ( $P > 0.05$ ). Both classification trees and random forest analysis identified mean weight placed on each foot and maximum pressure placed on a foot per step as the most important variables from the weight distribution and gait methods, respectively. The main difference between these very similar variables is the method used to obtain them. When both weight distribution and gait variables were analyzed together, only the mean weight placed on each foot was selected for inclusion in the final classification tree. Using the classification tree from force plate data, error

(misclassification of lameness status) rates were low ( $< 5\%$ ) in the first three days after lameness was induced in a rear foot. Error rates from days four to six range from 21.1 to 41.3, and error is above 50% at day seven. Error rates were a little higher when lameness was induced in a front foot, at 10.9 and 16.7% in days one and two, respectively, and climbed to 71.1% by day four. While a decrease to 29.2% did occur at day six, accuracy of lameness detection was still questionable after day three. Error rates were higher on day one post-induction using classification trees from gait data, 31.3% and 30.4% for rear and front feet, respectively. At day six, rear foot error rate was 29.8%, while front foot error rate was 60.9%. The differences between methods may be in part due to the amount of data generated by each system to calculate the average weight placed on each leg and maximum pressure placed on each foot. Sows remain on the force plate long enough to record 1800 measurements, whereas the GaitFour system records far fewer steps in less than one min required to walk a sow across. The force plate did not provide an advantage over visual lameness detection for the length of time post-induction that lameness could be detected. However, the scorers were aware of the treatments given to each sow, and this knowledge may have biased the scores. Furthermore, the force plate provides the advantages of more uniformity and less bias due to being an objective measurement and requiring less personnel training to collect accurate data and could be incorporated into an electronic feeding system for automated daily data collection (Abell et al., 2014). A similar study in which lameness was induced only in hind limbs (Mohling et al., 2014) also found that weight distribution and gait characteristic changes could be detected using force plate and GAITFour systems. Weight placed on the hoof in which lameness was induced decreased on day one following induction ( $P < 0.05$ ); to compensate, an increase



in weight bearing was observed in the sound hind hoof ( $P < 0.05$ ). On day 6 after induction, lameness was in the process of being resolved as weight placed on each hoof was intermediate and different ( $P < 0.05$ ) from the day before and the day after lameness induction. Maximum pressure exhibited a similar pattern in which the affected limb exerts less pressure while the opposite limb exerts more pressure at day 1 after induction ( $P < 0.05$ ). On day 6 after induction, when the left hind leg was induced, it began to resolve at an intermediate amount of pressure between day 1 and day -1 ( $P < 0.05$ ) while the right hind leg was not different from day 1 after induction ( $P > 0.05$ ). When the right hind leg was induced, the left hind leg did not show a significant change in pressure between day 1 and day 6 ( $P > 0.05$ ), but the right hind leg was back to a level not different from pre-induction ( $P > 0.05$ ). Stride time and stance time increased while stride length decreased ( $P < 0.01$ ) between pre-induction and day 1 post-induction. By day 6, stride time, stance time, and stride length had returned to pre-induction levels with only a couple exceptions that displayed intermediate values (Mohling et al., 2014).

The diversity of phenotyping methods has complicated comparisons between studies and rendered drawing actionable conclusions from the body of literature nearly impossible. Subjective scoring methods have been shown to have questionable reliability between observers, and extensive training and frequent retraining are required to achieve satisfactory reliability (Van Steenberg, 1989; Main et al., 2000; D'Eath, 2012). Objective measurements of body and toe sizes are relatively easy to obtain with the use of measurement devices, such as tape measures and calipers. Since these tools have been available for many years, objective measurements of size traits are available in the literature. Leg angles have proven more difficult to objectively measure, so objective

techniques have not been used for these traits with a few exceptions (Calabotta et al., 1982; Barczewski et al., 1990; Stock et al., 2017; Stock et al., 2018). Kinematics, accelerometers, and weight distribution assessments are objective methods of evaluating gait and lameness. Successful identification of lameness was reported using kinematics and weight distribution methods (Sun et al., 2011; Grégoire et al., 2013; Pluym et al., 2013a; Abell et al., 2014; Stavrakakis et al., 2014), while accelerometers had mixed results (Grégoire et al., 2013; Traulsen et al., 2016).

### **1.6.2 Genetic Parameters**

Several studies have estimated heritability of conformation traits (Bereskin, 1979; Webb et al., 1983; Huang et al., 1995; Fukawa et al., 2001; Serenius et al., 2001; Serenius and Stalder, 2004; Fernández de Sevilla et al., 2009b; Nikkilä et al., 2013b; Aasmundstad et al., 2014a; Aasmundstad et al., 2014b; Le et al., 2015; Stock et al., 2018; Pfeiffer et al., 2019). Heritability estimates were low to moderate and ranged from 0 to 0.4 when a sire or animal model was used. Heritability estimates are difficult to compare between studies as trait definitions, number of animals in the analysis, model used, genetic background, scoring system, sex, age, and weight of animals at the time of data collection, and other factors differ greatly. The average and range of heritability estimates obtained via sire and animal models were similar. However, greater heritabilities were observed when a sire-dam model was used compared to a sire model for some breeds and traits due to common environmental effects of littermates (Bereskin, 1979; Huang et al., 1995). Huang et al. (1995) estimated common environmental effects using the difference between dam and sire components, and reported  $c^2$  of 0.22, -0.02, and 0.27 for leg weakness in Landrace, Yorkshire, and Duroc, respectively. Leg weakness was scored at

the end of the performance testing period, during which littermates were housed together in groups of two, which could have led to an increased maternal common environmental effect. However, all three breeds were treated in the same manner, and this effect was only evident in Landrace and Duroc (Huang et al., 1995). Likewise, Bereskin (1979) also penned littermates together during the test period, but only observed a larger dam variance component for rear foot and leg scores but not front foot and leg scores. Common litter environment effects ranged from 0.05 to 0.20 in Serenius et al. (2001).

Method of analysis and terms included in the model also influence heritability estimates. Assuming normality of categorically scored variables can cause biased genetic parameter estimates, and trait means affect the error variances (Webb et al., 1983). When traits are assigned a categorical value, genetic parameters can be influenced by incidence and distribution between categories when a linear model is used (Le et al., 2016). Highly uneven distributions and low incidence can cause genetic parameter estimates to be inaccurate (Serenius et al., 2001). Serenius et al. (2001) observed that traits with the highest frequency also tended to have the highest heritability. Binomial data (fewer categories) is the most biased, but transformations can be done to reduce the bias (Webb et al., 1983). Le et al. (2016) estimated heritability of movement and overall score that were evaluated on a scale of 1 to 3 (3 optimum) in Swedish Yorkshire gilts at 100 kg of body weight using two different methods; the first method was the popular linear models and REML approach while the second was a Bayesian approach with a threshold model using a Gibbs sampler. This second approach is advantageous for non-normally distributed traits, and subjectively scored conformation traits often fall into that category due to most animals receiving favorable ratings. Higher heritability estimates were found

using the Bayesian threshold model with a Gibbs sampler compared to linear REML methods ( $h^2 = 0.10 \pm 0.01$  vs.  $0.07 \pm 0.01$  and  $0.14 \pm 0.01$  vs.  $0.12 \pm 0.01$  for movement and overall score, respectively). However, the REML-estimated heritabilities are on the observed scale while the Bayesian-estimated heritabilities are on the underlying normal scale, making them not directly comparable. Nonetheless, high correlations between EBV ranking using the different models suggest selection decisions and therefore genetic progress would not change between the two models, making either model acceptable for use.

Sows were scored at 100 kg of bodyweight and after first and second farrowing in Fernández de Sevilla et al. (2009b) and analyzed together using Bayesian threshold models to estimate heritability. Additionally, Bayes Factor (BF) was also computed to test for genetic contribution of conformation traits; it was defined as the ratio of probabilities between a model with and a model without an additive genetic effect. All traits had a BF larger than 1, except sickle-hocked leg in both Landrace and Large White (BF = 0.2 and 0.1, respectively). Splay-foot, plantigradism, and straight pasterns showed strong evidence of additive genetic determinism (BF = 18.6, 20.3, and 11.6, respectively) in Large White while splay foot and straight pasterns displayed strong evidence of additive genetic determinism (BF = 24.1 and 35.1, respectively) in Landrace.

Worsening leg conformation was observed with age in both breeds as the prevalence of all specific leg traits scored increased at first farrowing, except straight pasterns in the Landrace breed (Fernández de Sevilla et al., 2009b). Stock et al. (2018) also looked at conformation changes between gilt selection at 150 days of age and after parity 1 weaning prior to farrowing parity 2. However, the objectively measured

conformation traits in this study improved between the two time points; the hock became straighter (less sickle-hocked;  $P < 0.05$ ) while the knee and pastern angles obtained more flexion ( $P < 0.05$ ). Conversely, rear leg stance indicated that the feet were further under the center of the sow after weaning a litter than at selection ( $P < 0.05$ ), which is not a desirable trait. Sows that were further along in their second gestation at the time of evaluation had greater flex to the knee joint and had a rear stance position further under the center (linear  $P < 0.05$ ), though rear stance also exhibited a significant quadratic effect ( $P < 0.05$ ; Stock et al., 2018). Due to phenotypic changes in conformation over time (Fernández de Sevilla et al., 2009b; Stock et al., 2018), time of conformation trait observation may influence parameter estimates.

Nikkilä et al. (2013b) analyzed traits with intermediate optimums scored on a scale of 1 to 9. These traits (top line, front and rear pastern posture, and rear leg posture) were divided into two traits on a scale of 1 to 5. Analysis with the separate traits resulted in similar heritability and genetic correlations with other conformation traits as those obtained without dividing the trait. Front and rear legs turned were also initially scored on a scale of 1 to 9 with an intermediate optimum in this study but were recoded on a scale of 1 to 5 prior to analysis as there were very few gilts that had legs turned in to be given a score less than 5 (Nikkilä et al., 2013b).

Many studies also reported phenotypic and genetic correlations between conformational traits. Bereskin (1979) reported a phenotypic correlation between front and rear leg scores of 0.453 (significantly different from zero  $P < 0.01$ ) and a genetic correlation of  $0.805 \pm 0.138$  using a sire + dam model. Phenotypic correlations between the four conformation traits (motorics, front leg conformation, hind leg conformation, and

hind leg standing under) estimated by Aasmundstad et al. (2014b) were low ( $r_P = -0.01$  to  $0.23$ ), except motorics with hind leg conformation ( $r_P = 0.34$ ) and hind leg standing under ( $r_P = 0.33$ ). Genetic correlations between these traits were all higher and significantly different from zero, except between front leg conformation and hind leg standing under ( $r_G = -0.06$ ). Genetic correlations between other trait pairs ranged from  $0.28$  (hind leg conformation and hind leg standing under) to  $0.66$  (motorics and hind leg conformation; Aasmundstad et al., 2014b).

Pfeiffer et al. (2019) estimated genetic correlations between lameness, side view fore legs, side view rear legs, pastern fore legs, pastern rear legs, and claw scores. While most were in the moderate to high range, they also had high standard errors and, therefore, many were not significantly different from zero. Genetic correlations that were significantly different from zero were side view fore legs with pastern fore legs ( $r_G = 0.77 \pm 0.24$ ) and pastern hind legs ( $r_G = 0.70 \pm 0.34$ ) and pastern hind legs with side view hind legs ( $r_G = 0.71 \pm 0.24$ ), pastern fore legs ( $r_G = 0.67 \pm 0.23$ ), and claws ( $r_G = 0.79 \pm 0.34$ ; Pfeiffer et al., 2019).

Genetic correlations between conformational traits estimated by Le et al. (2015) were mostly moderate to high and all significantly different from zero except between overall score 1 and standing-under position ( $r_G = -0.22 \pm 0.16$ ) and overall score 2 and front leg quality ( $r_G = 0.14 \pm 0.08$ ) and standing-under position ( $r_G = 0.00 \pm 0.13$ ). Movement and overall score 1 were very highly positively correlated ( $r_G = 0.88 \pm 0.02$ ), but negatively correlated with the other conformation traits as these traits had higher optimum values compared to lower or intermediate optimum values. Standing-under position was also negatively correlated with all traits, aside from having non-significant

( $P > 0.05$ ) correlations with overall score 1 and overall score 2. Both standing-under position and toes quality had low optimum values yet were still moderately negatively correlated ( $r_G = -0.29 \pm 0.07$ ), indicating an unfavorable genetic association. All genetic correlations between movement 2, overall score 2, front and rear leg quality, and toes quality were positive. The highest genetic correlations occurred between movement 1 and overall score 1 and other traits; a genetic correlation of  $-0.82 \pm 0.06$  was observed between movement 1 and rear leg quality while overall score 1 had genetic correlations of  $-0.93 \pm 0.05$ ,  $-0.80 \pm 0.06$ , and  $-0.95 \pm 0.02$  with movement 2, toes quality, and rear leg quality, respectively. Other genetic correlations between structural traits in this study had absolute values between 0.30 and 0.75 (Le et al., 2015).

Fukawa et al. (2001) estimated genetic and phenotypic correlations between body length, withers height, chest girth, cannon circumference, cannon circumference score, claw score, front leg score, rear leg score, and gait score. Phenotypic correlations were low to moderate. Gait score had moderate phenotypic correlations with claw score and front and rear leg scores ( $r_P = 0.35, 0.41$ , and  $0.49$ , respectively). Claw score and rear leg score were also phenotypically correlated ( $r_P = 0.42$ ). Cannon circumference and cannon circumference score had a moderate phenotypic correlation ( $r_P = 0.34$ ) but a high genetic correlation ( $r_G = 0.77$ ). Cannon circumference score had moderate to high genetic correlations with front leg score and gait score ( $r_G = 0.49$  and  $0.55$ , respectively), but cannon circumference had very low genetic correlations with these traits ( $r_G = -0.06$  and  $0.02$ , respectively). Body length had a positive genetic correlation with withers height ( $r_G = 0.58$ ), but a negative genetic correlation with chest girth ( $r_G = -0.44$ ). Body length also had moderate to high genetic correlations with all leg structure traits ( $r_G = -0.42$  to  $-0.63$ ).

except rear leg score ( $r_G = -0.03$ ). Chest girth was positively genetically correlated with gait score ( $r_G = 0.49$ ) but negatively correlated with cannon circumference ( $r_G = -0.49$ ). Claw score was very highly genetically correlated with front and rear leg scores and gait score ( $r_G = 0.9$  to  $0.92$ ), and front and rear leg scores also had a very high genetic correlation ( $r_G = 0.94$ ; Fukawa et al., 2001).

Aasmundstad et al. (2014a) estimated phenotypic and genetic correlations between 11 conformation traits and osteochondrosis score. Most phenotypic correlations were low ( $r_P = -0.05$  to  $0.25$ ), with three reaching  $0.3$  or greater (front leg pastern side view and front leg knee side view,  $r_P = 0.39$ ; waddling hindquarters and hind leg standing under,  $r_P = 0.37$ ; front pastern side view and hind pastern side view,  $r_P = 0.30$ ). Genetic correlations ranged from  $-0.39$  to  $0.94$  and fell into all categories from near zero to extremely high. The highest genetic correlation was between front leg pasterns front view and front leg knee front view ( $r_G = 0.94 \pm 0.15$ ); this extremely high correlation indicates these may be the same trait genetically, but the lower phenotypic correlation between these traits ( $r_P = 0.23$ ) implies that the scorers view these traits as two separate traits. Front leg pastern front view was also highly genetically correlated with hind leg hock rear view ( $r_G = 0.57 \pm 0.26$ ) and hind leg pastern side view ( $r_G = 0.59 \pm 0.18$ ), while front leg knee front view was moderately correlated with osteochondrosis ( $r_G = 0.40 \pm 0.19$ ), hind leg hock rear view ( $r_G = 0.54 \pm 0.17$ ), and arched back ( $r_G = 0.45 \pm 0.26$ ). Arched back was moderately correlated with osteochondrosis ( $r_G = 0.52 \pm 0.22$ ), hind leg pasterns side view ( $r_G = 0.44 \pm 0.18$ ), and waddling hindquarters ( $r_G = 0.49 \pm 0.22$ ). High genetic correlations occurred between hind leg pasterns side view and front leg pasterns front view ( $r_G = 0.59 \pm 0.18$ ) and hind leg hock rear view ( $r_G = 0.54 \pm 0.17$ ), between



front leg pasterns side view and front leg knee side view ( $r_G = 0.69 \pm 0.10$ ) and hind leg pasterns side view ( $r_G = 0.49 \pm 0.09$ ), and between hind leg standing under and waddling hindquarters ( $r_G = 0.66 \pm 0.12$ ; Aasmundstad et al., 2014a).

Phenotypic correlations between overall leg action, buck-kneed forelegs, small inner claws on the fore and hind legs, fore legs turned out, and upright pasterns in the hind legs, were all low ( $r_P = -0.05$  to  $0.19$ ) in Finnish Landrace and Large White pigs with the exception of overall leg action and buck-kneed forelegs ( $r_P = 0.37$  and  $0.44$  in Landrace and Large White, respectively; Serenius et al., 2001). Genetic correlations between these traits ranged between  $-0.10$  and  $0.88$  in Landrace and  $-0.93$  and  $1.00$  in Large White. Overall leg action and buck-kneed forelegs also had high genetic correlations in both breeds ( $r_G = 0.88 \pm 0.07$  and  $0.98 \pm 0.09$  in Landrace and Large White, respectively). Upright pasterns in the hind legs were moderately to highly genetically correlated with all other traits ( $r_G = 0.29$  to  $0.83$ ) in Landrace but were lowly correlated with all other traits ( $r_G = -0.17$  to  $0.18$ ) in Large White except small inner claws ( $r_G = 0.69 \pm 0.23$ ). Small inner claws on the fore legs were highly genetically correlated with overall leg action ( $r_G = 1.00 \pm 0.28$ ), buck-kneed forelegs ( $r_G = 1.00 \pm 0.38$ ), and forelegs turned out ( $r_G = -0.93 \pm 0.46$ ) in Large White, but not Landrace ( $r_G = -0.10$  to  $-0.31$ ). Forelegs turned out was also highly genetically correlated with overall leg action ( $r_G = -0.68 \pm 0.25$ ) and buck-kneed forelegs ( $r_G = -0.61 \pm 0.18$ ) in Large White, while genetic correlations between these traits were low to moderate in Landrace ( $r_G = -0.22 \pm 0.39$  and  $0.25 \pm 0.29$ ). High standard errors and stark differences between breeds for most traits suggest these estimates should not be considered very reliable. Incidence

of conformational defects also influences linear model estimates of residual and phenotypic correlations (Serenius et al., 2001).

Nikkilä et al. (2013b) estimated genetic and phenotypic correlations between body conformation traits (body length, body depth, body width, rib shape, top line, and hip structure), front leg traits (front leg turned, buck knees, front pastern posture, front uneven toes, and front overall leg action), and rear leg traits (rear legs turned, rear leg posture, rear pastern posture, rear foot size, rear uneven toes, and rear overall leg action). Phenotypic correlations were low to moderate. Most genetic correlations between body structure traits were high, except between hip structure and other traits ( $r_G = -0.38$  to  $0.56$ ). Body width was negatively genetically correlated with all other body structure traits ( $r_G = -0.38$  to  $-0.95$ ), while all other body structure traits had positive genetic correlations with each other. The greatest genetic correlations were found between body length and body depth ( $r_G = 0.91 \pm 0.07$ ), body width and rib shape ( $r_G = -0.94 \pm 0.07$ ), body width and top line ( $r_G = -0.95 \pm 0.15$ ), and top line and rib shape ( $r_G = 0.92 \pm 0.13$ ). Genetic correlations between leg conformation traits were lower. Overall leg action was highly correlated with front pastern posture ( $r_G = 0.86 \pm 0.12$ ) but only moderately correlated with rear pastern posture ( $r_G = 0.27 \pm 0.24$ ). Front pastern posture was highly correlated with front foot size ( $r_G = 0.60 \pm 0.16$ ), and rear pastern posture was also highly correlated with rear foot size ( $r_G = 0.83 \pm 0.15$ ). Rear leg posture had high genetic correlations with rear pastern posture ( $r_G = 0.80 \pm 0.18$ ) and rear foot size ( $r_G = 0.82 \pm 0.18$ ). All other genetic correlations between leg structure traits were low (or moderate but with high standard errors). Most were fairly consistent between front and rear legs except front pastern posture was positively correlated with front legs turned ( $r_G = 0.30 \pm$

0.29) while rear pastern posture was negatively correlated with rear legs turned ( $r_G = -0.23 \pm 0.22$ ); however, with the large standard errors, both of these correlations could actually be near zero. When comparing front to rear leg conformation traits, the same phenomenon is observed in which front leg turned has negative genetic correlations with rear conformation traits, while rear leg turned has positive genetic correlations with front conformation traits; while these correlations range from -0.47 to 0.48, they have high standard errors and could also be near zero. Front and rear pastern posture and front and rear foot size had moderate to high genetic correlations that were significantly different from zero ( $P < 0.05$ ;  $r_G = 0.38 \pm 0.18$  and  $0.65 \pm 0.20$ ), while other front and rear trait pairs were lowly correlated. Buck knees and rear leg turned out had a moderate genetic correlation ( $r_G = 0.48 \pm 0.23$ ), but correlations for all other leg trait pairs were not significantly different from zero ( $P > 0.05$ ). Genetic correlations between body and leg conformation traits were low to moderate. Correlations between buck knees and body length ( $r_G = 0.60 \pm 0.19$ ), body depth ( $r_G = 0.82 \pm 0.11$ ), and body width ( $r_G = -0.62 \pm 0.17$ ) and front pastern posture and all body structure traits ( $r_G = 0.38$  to  $0.61$ ) except body width were significantly different from zero ( $P < 0.05$ ). Rear legs turned had correlations with all body size traits that were significantly different from zero ( $P < 0.05$ ;  $r_G = -0.78$  to  $0.72$ ), with body width being the only negative correlation. Rear leg posture was significantly ( $P < 0.01$ ) correlated with body length ( $r_G = 0.47 \pm 0.18$ ) and body depth ( $r_G = 0.52 \pm 0.17$ ), and overall leg action had significant ( $P < 0.05$ ) positive genetic correlations with all body conformation traits ( $r_G = 0.56$  to  $0.73$ ), except body width and rib shape (Nikkilä et al., 2013b). Genetic and phenotypic correlations between objectively

measured knee, hock, and pastern joint angles were small and most had standard errors greater than the estimate (Stock et al., 2018).

Webb et al. (1983) estimated genetic correlations between conformation traits scored in British Large White and Landrace boars at 27 and 91 kg of body weight. The genetic correlation between time points for the broad leg action trait, scored on a 5-point scale, was high in both Large White and Landrace ( $r_G = 0.69 \pm 0.14$  and  $0.80 \pm 0.19$ , respectively). Phenotypic correlations were lower ( $r_P = 0.15 \pm 0.01$  and  $0.12 \pm 0.01$ , respectively) in Large White and Landrace. More specific conformation traits scored on 3-point scales had low genetic correlations between time points, in part due to low and sometime negative sire variances for these traits. However, there were three traits with high genetic correlations that were significantly different from zero between the two time points. These genetic correlations ranged from 0.62 to 0.98 and were hind leg turned in in Landrace, hind leg turned out in Large White, and fore leg turned out in both breeds. Phenotypic correlations between the two time points for these traits were also low, ranging from 0.01 to 0.17 (Webb et al., 1983). When conformation traits were measured objectively at the time of gilt selection and post first parity, genetic correlations between the two time points were very high for front leg traits ( $r_G = 0.91$  for knee and  $0.99$  for front pastern), indicating that they could be considered the same trait. Genetic correlations between the two time points were much lower for rear leg traits ( $r_G = -0.06$  for hock and  $0.18$  for rear pastern); therefore, these are separate traits influenced by different genetic mechanisms (Stock et al., 2018).

No studies were found in which genetics of foot lesions were assessed in pigs. Nevertheless, the genetics of foot lesions has been studied in dairy cattle, particularly the

heritability of foot lesions. Heritability estimates of foot lesion in dairy cattle range from 0.0005 to 0.521 (van der Waaij et al., 2005; Onyiro et al., 2008; Laursen et al., 2009; van der Linde et al., 2010; Buch et al., 2011; Chapinal et al., 2013; Oberbauer et al., 2013; Schöpke et al., 2013; van der Spek et al., 2013; Dhakal et al., 2015; Schöpke et al., 2015; Malchiodi et al., 2017), though most estimates were in the lower half of this range. There are several reasons for the wide range in heritability estimates. First, these estimates are for multiple types of foot lesions. It is to be expected that heritability would not be the same for all lesion types. Additionally, the traits were defined and phenotyped differently between studies. Lesions with similar genetic causes tended to have moderate to high genetic correlations (Buch et al., 2011), but genetic correlations were low between lesions with different causes (Buch et al., 2011; Chapinal et al., 2013). Thus, grouping lesions that have different etiology results in a lower heritability estimates due to low genetic correlation between the lesion types. Increasing the complexity of trait definition rather than binary and utilizing repeated measurements (for some trait definitions) resulted in higher heritability estimates. Schöpke et al. (2015) demonstrated this with digital dermatitis. When a binary trait definition was used, heritability was estimated as 0.194 and 0.203 using the first observation only and 0.288 and 0.130 when at least three measurements per cow were considered when the binary trait was defined as no lesion vs. any stage of the lesion and no lesion or an inactive lesion vs. active lesion, respectively. Categorical trait definitions with more than two categories to better account for different stages of lesions yielded similar results as binary trait definitions with repeated measures with estimates ranging from 0.234 to 0.268. However, heritability increased to 0.423 when digital dermatitis was treated as a continuous trait using a score calculated based on

changes in lesion status and to 0.521 when a categorical analysis was utilized with categories of no active lesions vs. active lesion at one observation only vs. multiple active lesions (Schöpke et al., 2015). Population differences, including differences in genetics, prevalence of lesions, and environment and management, also contributed to variability in heritability estimates. Studies which had higher prevalence of foot lesions also tended to have higher heritability estimates. Prevalence was also affected by phenotyping method and was higher when mild and subclinical cases were documented than when only severe clinical cases were recorded. Model differences also impacted heritability estimates. Threshold models resulted in higher heritability estimates than linear models. However, this is due to the models producing results on a different scale. The results of threshold models are on the underlying scale while the results of linear models are on the observed scale. After a transformation to the other scale, both models produced similar results (Malchiodi et al., 2017). The type of model used also had minimal impacts on sire ranking (Spearman's rank correlation  $\leq 0.94$ ; Malchiodi et al., 2017). Finally, the use of genomic information increased heritability of foot lesions (Dhakai et al., 2015).

As foot lesions have low heritability and are difficult and time consuming to record, genetic correlations were identified between foot lesions and potential indicator traits, including locomotion and conformation (Table 1.6). Most genetic correlations are favorable, particularly when individual lesion types are considered rather than composite lesion scores. When conformation traits were included as indicator traits in a foot health index, the reliability of the index increased from 53% to 59% (van der Linde et al., 2010). However, phenotyping foot lesions is still necessary as reliability dropped to 24% if the index only included conformation traits (van der Linde et al., 2010).

Table 1.6. Genetic correlations between foot lesions and potential indicator traits. Genetic correlations shown in green indicate a favorable correlation, correlations shown in red indicate an unfavorable correlation, and correlations shown in black are neither favorable nor unfavorable due to an intermediate optimum in the indicator trait.

Foot Lesion	Indicator Trait	Genetic Correlation	Source
<b>Claw lesions</b>	Locomotion	0.46	Laursen et al. (2009)
<b>Claw lesions</b>	Rear leg rear view	0.21	Laursen et al. (2009)
<b>Infectious</b>	Feet and leg	-0.06	Dhakai et al. (2015)
<b>Infectious</b>	Rear leg set	0.14	Dhakai et al. (2015)
<b>Infectious</b>	Rear leg rear view	-0.25	Dhakai et al. (2015)
<b>Noninfectious</b>	Rear leg set	0.13	Dhakai et al. (2015)
<b>Noninfectious</b>	Foot angle	0.1	Dhakai et al. (2015)
<b>Noninfectious</b>	Rear leg rear view	-0.09	Dhakai et al. (2015)
<b>DD<sup>1</sup></b>	Locomotion	-0.67	Onyiro et al. (2008)
<b>DD<sup>1</sup></b>	Legs and Feet	-0.63	Onyiro et al. (2008)
<b>DD<sup>1</sup> (P1)<sup>2</sup></b>	Feet and leg	-0.51	van der Linde et al. (2010)
<b>DD<sup>1</sup> (P2+)<sup>3</sup></b>	Feet and leg	-0.27	van der Linde et al. (2010)
<b>DD<sup>1</sup> (P1)<sup>2</sup></b>	Rear leg rear view	-0.32	van der Linde et al. (2010)
<b>DD<sup>1</sup> (P2+)<sup>3</sup></b>	Foot angle	0.19	van der Linde et al. (2010)
<b>IDD<sup>4</sup></b>	Locomotion	-0.6	Laursen et al. (2009)
<b>IDD<sup>4</sup> (P1)<sup>2</sup></b>	Feet and leg	-0.44	van der Linde et al. (2010)
<b>IDD<sup>4</sup> (P2+)<sup>3</sup></b>	Feet and leg	-0.34	van der Linde et al. (2010)
<b>IDD<sup>4</sup> (P1)<sup>2</sup></b>	Rear leg rear view	-0.23	van der Linde et al. (2010)
<b>IDD<sup>4</sup> (P1)<sup>2</sup></b>	Rear leg side view	0.25	van der Linde et al. (2010)
<b>IDD<sup>4</sup> (P1)<sup>2</sup></b>	Foot angle	-0.25	van der Linde et al. (2010)
<b>Sole ulcer (P1)<sup>2</sup></b>	Locomotion	-0.24	van der Linde et al. (2010)
<b>Sole ulcer (P2+)<sup>3</sup></b>	Locomotion	-0.3	van der Linde et al. (2010)
<b>Sole ulcer (P2+)<sup>3</sup></b>	Feet and leg	-0.34	van der Linde et al. (2010)
<b>Sole ulcer</b>	Rear leg side view	0.41	van der Linde et al. (2010)
<b>IDH<sup>5</sup></b>	Locomotion	-0.53	Laursen et al. (2009)
<b>IDH<sup>5</sup> (P1)<sup>2</sup></b>	Feet and leg	-0.4	van der Linde et al. (2010)
<b>IDH<sup>5</sup> (P2+)<sup>3</sup></b>	Feet and leg	-0.36	van der Linde et al. (2010)
<b>IDH<sup>5</sup> (P1)<sup>2</sup></b>	Rear leg rear view	-0.26	van der Linde et al. (2010)
<b>IDH<sup>5</sup> (P2+)<sup>3</sup></b>	Rear leg rear view	-0.3	van der Linde et al. (2010)
<b>Foot rot</b>	Locomotion	-0.44	Laursen et al. (2009)

<sup>1</sup>DD = digital dermatitis

<sup>2</sup>P1 = parity 1

<sup>3</sup>P2+ = parity 2 or greater

<sup>4</sup>IDD = interdigital dermatitis

<sup>5</sup>IDH = interdigital hyperplasia

In addition to differences in phenotyping methods previously discussed, heritability estimates are difficult to compare between studies due to differences in model effects, type of model used, and prevalence of the trait or the extent to which the full scale was used. Genetic correlations tended to be higher than phenotypic correlations between conformation traits, with some pairs of traits showing high genetic correlations. However, many trait pairs had no genetic correlation. Genetic correlations between conformation traits evaluated at different times of life are needed to determine if phenotypes obtained before selection are useful to predict genetic merit throughout life. Genetic correlation estimates between time points were high for some conformation traits, but low for others (Webb et al., 1983; Stock et al., 2018).

### **1.6.3 Phenotypic Selection**

A phenotypic selection experiment was performed for front leg weakness in Duroc swine (Draper et al., 1988; Goedegebuure et al., 1988; Rothschild and Christian, 1988; Rothschild et al., 1988; Draper et al., 1992). Three lines were developed, a high structural soundness line with the least amount of front leg weakness, a low structural soundness line with the most front leg weakness, and an intermediate control line. Selection continued for five generations within each line and was based on front structure scores evaluated at 100 kg of body weight. In generation 5, pigs ( $n = 3598$ ) were scored for front structure, front movement, and other structural traits on a scale of 1 to 9 (9 optimum) by three independent scorers blind to the line of each pig. Differences between lines existed for front structure ( $P < 0.01$ ; 3.20, 5.47, and 7.74 for low soundness, control, and high soundness, respectively; Rothschild and Christian, 1988). Heritability for improved front structure and increased front weakness was  $0.29 \pm 0.06$  and  $0.42 \pm 0.04$ ,



respectively. Rear leg scores were also influenced by selection on front leg weakness; the low soundness line had smaller rear toes, poorer rear leg movement, and poorer rear hock scores ( $P < 0.01$ ) than the control and high soundness lines. This large response after only five generations of selection suggests there is moderate to high genetic control of front leg weakness in Duroc swine (Rothschild and Christian, 1988). Correlated responses to selection were also measured for growth traits and reproductive performance (Rothschild et al., 1988). No differences in lines were observed for ADG and days to 104 kg, but the high soundness line had more backfat ( $P < 0.05$ ). Fertility was decreased in the low soundness line as gilts had lower pregnancy rates as did all females mated to low line boars. The control line, however, had superior performance in other reproductive traits (Rothschild et al., 1988). Ten pigs of each sex and line were scored for osteochondrosis after slaughter (Goedegebuure et al., 1988). The high soundness line had lower osteochondral lesion scores for the proximal radius/ulna than the control and low soundness lines ( $P < 0.05$ ); however, significant differences were not observed at any other joints or growth plates assessed (Goedegebuure et al., 1988). Additional carcass composition data and bone and muscle weights and measurements from the right front leg were collected after slaughter at 118 kg in 14 gilts from the low and high structural soundness lines and 16 gilts from the control line (Draper et al., 1992). Low line pigs had significantly longer carcasses than control pigs ( $P < 0.05$ ) but were not different from high line pigs. No differences between lines were observed for carcass yield or loin eye area, but the high line pigs tended to have more backfat than the low line pigs ( $P < 0.09$ ). Weights were taken on five arm muscles and eight forearm muscles. Significant weight differences ( $P < 0.05$ ) existed for one arm muscle (biceps brachii) and two forearm

muscles (extensor carpi radialis and lateral digital extensor). In all cases, the low structural soundness line had heavier muscles than the control and high structural soundness lines. Muscle lengths were measured in five shoulder, five arm, and seven forearm muscles. Significant differences between lines ( $P < 0.05$ ) were present in one shoulder muscle (subscapularis), two arm (biceps brachii and tensor fascia antebrachii), and one forearm muscle (common digital extensor). The arm muscle lengths followed the same pattern as muscle weights in which significant differences were the result of longer muscles in the low line compared to control and high lines. The low line had the longest subscapularis muscle as well, but only the control line was significantly shorter. The common digital extensor muscle was longer in high line gilts compared to the control and low lines. No differences ( $P > 0.05$ ) were observed between lines for the weight of any of the six bones measured. Differences between lines ( $P < 0.05$ ) were observed for the scapula thickness, metacarpal bone length, and humerus length, head width, and head angle, but the direction of effects was not consistent. These differences appear unrelated to growth rates and could be the result of bone size ratios required for optimal articulation in the high structural soundness line. Differences in muscles and bones are related to each other, and the authors hypothesize that the structural differences create biomechanical imbalances that result in leg weakness (Draper et al., 1992). Angles of the shoulder, elbow, carpal, and hock were also measured with a goniometer on ten boars and ten gilts from each line approximately five to nine days after reaching 100 kg in generation 5 (Draper et al., 1988). Resting joint angles and the angles at maximum flexion and extension were determined for each joint. The degrees of flexion and extension were calculated by subtracting the maximum angle from the resting angle, and the maximum

flexion and extension angles were summed to obtain total degrees of motion. Significant differences in resting angles were observed between lines for the elbow ( $P < 0.05$ ), carpal ( $P < 0.01$ ), and hock ( $P < 0.05$ ) joints, but not the shoulder joint ( $P > 0.05$ ). The high structural soundness line had a smaller resting elbow joint angle than the control and low structural soundness lines, while the low structural soundness line had a smaller resting carpal joint angle than the control and high structural soundness lines. These differences indicate the low structural soundness line pigs had straight legs at the elbow and buck-knees, which shifted the center of gravity forward and altered the direction of forces on the skeletal structure. The hock joint resting angle was greater in the low structural soundness line than in the control and high structural soundness lines, indicating a straighter rear leg in this line. The maximum extension of the carpal joint was less for the low structural soundness line than the control and high structural soundness lines ( $P < 0.01$ ). The degrees of extension and flexion of the elbow joint differed between lines ( $P < 0.05$ ). The low structural soundness line had less extension than the high structural soundness line with the control line intermediate, while the high structural soundness line had lower flexion than the control line with the low line intermediate. These differences are likely related to the differences in resting angle of the elbow joint between lines.

Asymmetry between the right and left legs existed for the resting angles of the elbow ( $P < 0.001$ ) and carpal ( $P < 0.01$ ) joints, maximum flexion of the elbow joint ( $P < 0.05$ ), and flexion ( $P < 0.01$ ), total movement ( $P < 0.01$ ), and maximum extension ( $P < 0.05$ ) of the carpal joint. The right side had greater resting angles and more flexion, extension, and movement than the left side. Leg lengths were also measured, but no differences were observed between lines and sides of the body (Draper et al., 1988).

While they were not phenotypic selection experiments for conformation, studies have assessed the impacts of selection for average daily gain (Woltmann et al., 1995) and lean tissue growth rate (Stern et al., 1995) on structural soundness. Divergent selection for ADG between nine wk of age and 100 kg bodyweight was performed on mixed breed lines of pigs (Woltmann et al., 1995). In approximately generations 4 to 5, pigs from each line were also scored for front leg structural soundness, similar to that performed by Rothschild and Christian (1988), on a scale of 1 to 8, with 8 being superior leg structure. There were no differences in front leg soundness scores between lines (fast and slow growth;  $P > 0.35$ ; Woltmann et al., 1995). Phenotypic correlations were low but significantly different from zero ( $P < 0.01$ ) between front leg structural soundness score and ADG during finishing (55 to 100 kg bodyweight;  $r_P = 0.214$ ), overall ADG ( $r_P = 0.145$ ) and average backfat thickness at 105 kg ( $r_P = 0.095$ ). The phenotypic correlation between front leg structural soundness score and ADG during the growing phase (9 wk of age to 55 kg bodyweight) was not significantly different from zero ( $r_P = 0.011$ ; Woltmann et al., 1995). In another phenotypic selection experiment, selection was for increased lean tissue growth rates in two lines fed either a high protein or low protein diet during performance testing from 25 to 90 kg of bodyweight (Stern et al., 1995). At the end of the performance test, leg weakness scores were assigned on a scale of 1 to 5 based on the gait or walking ability of the pig in which 1 was stiff and slow movement (worst) while 5 was easy and quick movement (best). Animals not selected as parents for the next generation were slaughtered at approximately 103 kg of bodyweight, and osteochondrosis was scored one knee and one elbow joint. Data was available from pigs in generations 0 to 4. Significant differences between lines existed for leg weakness score in generations 0 and

2 ( $P < 0.05$ ) and for osteochondrosis in the elbow in generations 0 ( $P < 0.001$ ), 3 ( $P < 0.05$ ), and 4 ( $P < 0.01$ ) and knee in generation 0 ( $P < 0.01$ ). The low protein line had more favorable scores in all instances. Heritability estimates of leg weakness score and osteochondrosis in the elbow and knee in these lines were moderate and ranged from 0.16 (leg weakness in the low protein line) to 0.49 (osteochondrosis in the knee in the low protein line). Genetic correlations between leg weakness score and osteochondrosis were low to moderate with high standard errors, and phenotypic correlations were low. Genetic correlations between structural traits (leg weakness score and osteochondrosis in the elbow and knee) and growth traits (lean tissue growth rate, growth rate, and lean percentage) were low to moderate with high standard errors. However, a high negative genetic correlation was observed between leg weakness score and lean tissue growth rate ( $r_G = -0.50 \pm 0.18$ ) in the high protein line, but this correlation was near zero in the low protein line ( $r_G = 0.01 \pm 0.22$ ). Phenotypic correlations were all low and most were not significantly different from zero. The genetic trend for leg weakness score was not significant in the low protein line, indicating no change in leg weakness over time because of selection for high lean tissue growth rate on a low protein diet. A small but significant ( $P < 0.01$ ) genetic trend was observed in the high protein line, in which selection for high lean tissue growth rate resulted in a deterioration of leg weakness score over time with a linear regression on generation number of -0.03 (Stern et al., 1995).

Phenotypic selection experiments have shown selection for conformation does change specific leg angles and size and ratios of some bones and muscles. While not the case with the traits discussed in these phenotypic selection experiments, many conformation traits previously discussed had measuring systems that produced

intermediate optimums. In these cases, a direction for selection must be chosen. This decision is based mostly on where the population mean is; selection should move the population mean in the direction that gets it closer to the optimum (Aasmundstad et al., 2014a). Another consideration is whether one extreme is worse than the other. For example, in the case of pastern joints angles, weaker pasterns are thought to be better than upright pasterns (Aasmundstad et al., 2014a). Aasmundstad et al. (2014a) also recommended including traits in a breeding goal rather than performing phenotypic threshold selection for them. Because they tend to have low heritabilities, phenotypic threshold selection would result in decreased genetic gain. Furthermore, incorporation of conformation traits into the Norsvin breeding goal has shown successful genetic improvement of these traits while maintaining higher overall genetic gain (Aasmundstad et al., 2014a). Phenotypic selection experiments highlight the importance of including conformation in the breeding goal to ensure change occurs in the right direction as phenotypic selection experiments have demonstrated correlations between conformation and other economically important traits.

#### **1.6.4 Genome Wide Association Studies and Candidate Gene Exploration**

Several studies have attempted to identify quantitative trait loci (QTL) for conformation traits in pigs. Lee et al. (2003) used 308 Large White x Meishan F<sub>2</sub> pigs and 111 microsatellite markers located throughout the genome to identify QTL for front legs score, front feet score, back legs score, back feet score, gait score, osteochondrosis lesions, and physis score. Only one QTL reached the genome-wide significance level; this was a QTL for gait score on SSC1 with an additive effect, but no dominance effect. Nominal significant QTL were identified on all chromosomes except SSC11, 12, 17, and

X. Chromosomal regions on SSC1, 13, 14, and 15 appeared to influence multiple traits, while other QTL were isolated effects. Quantitative trait loci for front leg score ( $n = 1$ ), front feet score ( $n = 1$ ), back feet score ( $n = 2$ ), and back leg score ( $n = 2$ ), and physis score ( $n = 1$ ) were located near the genome-wide significant QTL for gait score on SSC1 (52 to 131 cM). Chromosome 13 contained QTL for physis score, front feet, and front legs very close to each other (53 to 58 cM) and two QTL for gait at 0 and 72 cM. Chromosome 14 contained QTL for front (4 cM) and back (8 cM) feet, front (21 cM) and back (38 cM) legs, and gait (109 cM). Quantitative trait loci for back feet and back legs were located on SSC15 at 8 and 14 cM, respectively. Additional QTL were identified on other chromosomes for front legs ( $n = 1$ ), front feet ( $n = 2$ ), back legs ( $n = 5$ ), gait ( $n = 6$ ), osteochondrosis ( $n = 2$ ), and physis score ( $n = 6$ ; Lee et al., 2003).

Fan et al. (2009) selected functional candidate genes with functions related to skeletal pattern development, bone matrix biosynthesis, osteoclast and osteoblast differentiation, calcium and phosphorus metabolism, and bone related signaling pathways for association analysis with 17 conformation traits. Conformation traits consisted of body conformation traits relating to body size (length, depth, and width) and shape (hip structure, rib shape, and top line), feet and leg traits on the front (legs turned, buck knees, pastern posture, foot size, and uneven toes) and rear (legs turned, weak/upright legs, pastern posture, foot size, and uneven toes), and overall leg action. Functional candidate genes ( $n = 95$ ) were sequenced in pooled samples from extreme phenotypes, and 119 SNPs from these genes were identified and genotyped. Sixty-nine SNPs from 54 genes were significantly ( $P < 0.05$ ) associated with at least one trait. Genes *COL1A2* and *CALCR* included SNPs that were significantly associated with hip structure ( $P < 0.001$ )

and both front ( $P < 0.05$ ) and rear ( $P < 0.01$ ) pasterns. These genes are located adjacent to each other on SSC9; three haplotypes accounting for 98% of the pigs tested were identified in this region, and individuals with a specific major haplotype (60.9%) had significantly different overall leg action, front and rear pasterns, and PC 1 of feet and leg structure ( $P < 0.01$ ) than other individuals with any other haplotype. Additionally, SNPs in four more genes were significantly associated with both front and rear pasterns ( $P < 0.05$ ; Fan et al., 2009). Fan et al. (2011) performed a genome-wide association study (GWAS) with the same conformation traits using the Porcine SNP60 Beadchip. Fourteen QTL were identified for overall leg action. Several QTL were identified for body conformation traits. These regions differed between traits; however, there was a common QTL for three body size traits on SSC1 (270 Mb). Feet and leg conformation traits had many small effect QTL that differed between traits. Cluster analysis showed enriched functions of bone and cartilage development, muscle development, and insulin pathway in these regions. Overall, *BMP2* emerged as an interesting candidate gene as two SNPs within this gene were associated with body length, depth, and width, front and rear pasterns, rib shape, and buck knees (Fan et al., 2011).

Guo et al. (2009) evaluated leg and gait scores on the front and rear in White Duroc x Erhualian F<sub>2</sub> pigs. Microsatellite markers ( $n = 183$ ) located across the genome were used for GWAS. Additive effects were displayed by QTL in 38 genes while QTL in 14 genes had dominance effects. No QTL were identified for leg score at 76 days of age, but all other traits had at least two QTL. Regions on SSC4 and 7 showed pleiotropic effects on five and eight traits, respectively. Otherwise, most QTL differed between traits, even between the same leg and gait scores evaluated at two different time points (Guo et



al., 2009). These same traits were evaluated in the same White Duroc x Erhualian F<sub>2</sub> line as well as a Suta line (a synthetic breed derived from Duroc and Taihu; Guo et al., 2013). Genotyping was performed with the porcine SNP60 Beadchip, and GWAS were performed on each population separately as well as with both populations combined. Twelve significant QTL were identified in this study (Guo et al., 2013); 11 confirmed QTL identified in Guo et al. (2009). The previously identified QTL on SSC7 was still present in all populations for *biceps brachii* length and rear gait score and in F<sub>2</sub> and the combined population for front gait score (Guo et al., 2013). However, the top SNP differed between populations and traits and was located from 23.23 to 44.66 Mb on SSC7. There were significant QTL on SSCX for *biceps brachii* width in all three populations (Guo et al., 2013) and in Guo et al. (2009), but the top SNP also differed between populations, ranging from 65 to 95 Mb (Guo et al., 2013).

Uemoto et al. (2010) genotyped 447 microsatellite markers in five purebred Landrace sires, and polymorphic microsatellite markers (n = 110-128) were genotyped in 522 half-sib female progeny that were also scored for conformation traits of total leg score, total feet score, total front score, total rear score, and total score. No genome-wide significant QTL were identified, but nine chromosome-wide significant QTL were detected. Rear leg score had two chromosome-wide significant QTL while all other traits had one except total feet score. Three QTL were near QTL found by Lee et al. (2003) and Guo et al. (2009). The proportion of the phenotypic variance explained by each of the QTL identified in this study ranged from 0.07 to 0.13 (Uemoto et al., 2010).

Laenoi et al. (2011) genotyped F<sub>2</sub> Duroc x Pietrain pigs (n = 310) for 79 microsatellites and three SNPs in functional candidate genes for cartilage quality. Front

and rear leg and feet scores, osteochondrosis at four locations, and three bone mineralization traits were tested. Eleven chromosome-wide significant QTL were identified for front foot score ( $n = 2$ ), rear leg score ( $n = 2$ ), osteochondrosis on the head of the humerus ( $n = 3$ ), osteochondrosis on the condyles medialis humeri ( $n = 1$ ), osteochondrosis on the condyles medialis femori ( $n = 1$ ), bone mineral density ( $n = 1$ ), and bone mineral contents ( $n = 1$ ). These QTL explained 4.20 to 6.82% of the phenotypic variance for their respective traits, and the majority had dominance rather than additive effects. Most QTL only influenced one trait; however, QTL for osteochondrosis on chromosomes 2, 3, and 6 had overlapping 95% confidence interval locations with two QTL for bone mineralization and one QTL for rear leg score, respectively, though confidence intervals were rather large (43-171.5 cM; Laenoi et al., 2011).

Associations between three functional candidate genes, *MMP3*, *TGF $\beta$ 1*, and *COL10A1*, and leg traits, osteochondrosis, and bone mineralization were also assessed in this Duroc x Pietrain population ( $n = 310$ ) and in a commercial population including Large White, Landrace, and Duroc genetics ( $n = 299$ ; Laenoi et al, 2012). Commercial animals were scored for osteochondrosis in three locations, but phenotypes were not available for any other traits in this population. One SNP was identified in each gene. After correction for multiple testing, no SNPs were significantly associated with either trait in either population. However, before the correction, the SNP in *MMP3* was associated ( $P < 0.05$ ) with osteochondrosis at the head of the femur in the Duroc x Pietrain population, and the osteochondrosis score in this location was doubled in one homozygote compared to the other (Laenoi et al., 2012).

Le et al. (2017) performed a GWAS for four conformation traits in three Danish pig breeds. Landrace (n = 23,898), Yorkshire (n = 24,130), and Duroc (n = 16,524) pigs were scored for front leg, hind leg, and back quality and genotyped with the Porcine SNP60 BeadChip or one of two custom chips then imputed to include all Porcine SNP60 BeadChip SNPs. This analysis was performed on all three breeds and four traits separately, then the breeds and traits were combined into two meta-analyses. The Landrace breed had a total of 14 significant QTL; one was for hind leg quality, five were for back quality, and eight were for overall conformation. The most significant SNP was located on SSC7 at 36.2 Mb and explained 0.2% of the phenotypic variance of back quality. Twelve QTL regions were identified in Yorkshire; one was for front leg quality, three were for hind leg quality, one was for back quality, and seven were for overall conformation. The most significant SNP was located at SSC1 (199.4 Mb) and explained 0.2% of the genetic variance for overall conformation. In Duroc, 13 QTL were identified; two were for front leg quality, one was for hind leg quality, two were for back quality, and eight were for overall conformation. The most significant QTL in Duroc peaked between 100.2 and 100.4 Mb on SSC3 and explained 0.9% of the phenotypic variance for back quality. Some QTL regions were significant for multiple traits within breeds. However, the only common QTL region between breeds was a region on SSC7 that was associated with overall conformation in both Yorkshire and Duroc. Within breed multi-trait meta-analysis was able to detect more significant SNPs than single trait analyses due to increased power as this analysis was able to account for the high genetic correlations between the four conformation traits. Across breed single-trait meta-analysis identified 36 significant QTL regions. Positional candidate genes identified near the QTL regions in

this study were associated with bone and muscle development, growth promotion, vertebrae and rib development, the neuronal system, and fat metabolism (Le et al., 2017).

Lee et al. (2019) performed GWAS for body length, body height, and total teat number using EBV and deregressed EBV (DEBV) either with or without removing parent average effects as response variables in Korean Yorkshire pigs ( $n = 1,857$ ). One Mb windows that explained at least 1% of the additive genetic variance and SNP with a model frequency of at least 90% were considered informative. Various modelling approaches were tested for accuracy, including BayesB and BayesC with values of  $\pi$  of 0.5, 0.8, 0.9, 0.99, and the estimated  $\pi$  value obtained with the BayesC $\pi$  method. After SNP effects were estimated in a training population, accuracy was assessed in five validation populations with a bivariate animal models including molecular breeding values (sum of all estimated SNP effects) and EBV or DEBV including or excluding parent average effects as response variables. Informative SNP markers and windows were similar between the response variables, Bayesian methods, and  $\pi$  values. Using BayesB with  $\pi = 0.9$  and DEBV including parent average effects, the number of informative windows and SNPs for body length, body height, and total teat number were three and four, four and six, and four and five, respectively. The most significant SNP for both body length and body height and was located on SSC14 (21.7 Mb). It is located near two candidate genes, *NEK1* and *SH3RF1*. The most informative window explained 6.22% of the genetic variance for body height, and it contained 15 SNPs between 16.46 and 16.99 Mb on SSC17. The most informative window for body length was located nearby on SSC17 (17.10-17.92 Mb) and explained 5.33% of the genetic variance. The *BMP2* gene is located near these regions (Lee et al., 2019) and included two SNP shown to be

associated with body length and body depth by Fan et al. (2011). Genomic accuracy of the different  $\pi$  values ranged from 0.976 to 0.999 depending on the trait and response variable used, and no significant differences were observed between the different  $\pi$  values (Lee et al., 2019). The BayesB models resulted in slightly higher genomic accuracy than BayesC because it allowed for heterogeneous marker variance values rather than a homogeneous marker variance, though the differences between accuracies were within the ranges of their standard errors for most traits and  $\pi$  values. Using EBV as a response variable resulted in lower accuracy than if DEBV was used for all traits. Accuracy was improved even more if the parent average effect was accounted for in the DEBV. Using a BayesB model with a  $\pi$  of 0.99 and DEBV including the parent average effect as a response variable, genomic accuracies were 0.60, 0.52, and 0.51 for body length, body height, and total teat number, respectively (Lee et al., 2019).

While no GWAS for foot lesions in pigs have been conducted to our knowledge, van der Spek et al. (2015) performed a GWAS for several foot lesion types in dairy cattle. Cows ( $n = 1,771$ ) with genotypes and phenotypes (31% with repeated records) were used in the study. An independent set of 185 genotyped bulls with 6,824 phenotyped daughters was used for validation. In total, ten significant and 45 suggestive SNP were identified. These SNP spanned the entire genome, and rather than being in clusters surrounding a QTL, many were the only significant or suggestive SNP in the region. Only three of the suggestive SNP were validated in the independent population. Low validation success could be due to overestimation of SNP effects caused by low minor allele frequency (van der Spek et al., 2015).

Several QTL have been identified for conformation traits in pigs, some of which overlap between traits and studies. However, many more are not pleiotropic and have not been validated in other populations. Furthermore, few SNP maintained full significance after correction for multiple testing, and phenotypic variance explained by significant SNP was low. This suggests conformation is highly polygenic and controlled by many genes with small effects. Focusing on the entire genome using a genomic selection approach may result in more genetic progress than a marker-assisted selection approach targeting a small number of genetic variants.

### **1.6.5 Genomic Selection**

The value of genomic selection is likely to be greater for lowly heritable traits as genomic data adds relatively more information to predict breeding value than when heritability is higher (Bouquet and Juga, 2013; Wiggans et al., 2017). In addition to increased accuracy, genomic selection also has the potential to reduce generation interval because it enables the estimation of Mendelian sampling without phenotypic information (Bouquet and Juga, 2013). Furthermore, it can be useful to select on new phenotypes or traits that are difficult or expensive to measure (Bouquet and Juga, 2013; Knol et al., 2016), expressed late in life (Knol et al., 2016; Wiggans et al., 2017), or only expressed in one sex (Knol et al., 2016). The dairy industry has implemented genomic selection schemes which include conformation traits (Wiggans et al., 2017) and confirmed these advantages. Reliability increased for all traits, and even doubled for many traits, included in U.S. Holstein genetic evaluations using genomic information compared to just parent average. Specifically for conformation traits (stature, strength, body depth, dairy form, rump angle, rump width, rear legs side view, rear legs rear view, foot angle, and feet and

legs composite), reliabilities increased from 36.7 to 38.8% using parent average to 56.5 to 75.8% using genomic information; the increases in reliability for each trait ranged from 19.4 to 36.7% (Wiggans et al., 2017).

While the swine industry was slower to adopt genomic selection schemes, single step genomic evaluations have been implemented by leading swine breeding companies. As a result, increased accuracy has been shown for traits such as teat number and post-weaning mortality, while other traits, such as culling after first litter, have not benefitted as greatly (Knol et al., 2016). Biological differences between swine and dairy cattle as well as differences in industry structure necessitate cost-benefit analysis in swine. Generation interval is naturally shorter in swine, and one bull can breed more cows than a boar is typically utilized to breed sows. Therefore, selection intensity and accuracy are already high due to increased progeny testing in the dairy industry. The advantage of genomic selection for the dairy industry is the ability to increase accuracy at a younger age allowing earlier selection to greatly reduce generation interval. In pigs, without as much relative information and an already shorter generation interval, the main advantage of genomic evaluation is through improved accuracy (Samorè et al., 2015; Knol et al., 2016).

Several simulation and field data studies have also been performed to further investigate potential benefits of genomic selection within the swine breeding system as well as consider various factors and methods of application that influence the economic success of a genomic selection program. In simulations of a low heritability trait ( $h^2 = 0.1$ ) comparing conventional best linear unbiased prediction (BLUP), a progeny testing scheme, and various proportions of males and females genotyped, genotyping both males

and females was advantageous (Lillehammer et al., 2011). Genotyping more females resulted in a linear increase in female accuracy as a greater proportion of the females had a GEBV and the reference population was larger. Genetic gain also increased as more females were genotyped, but it was not linear as genotyping more females was more advantageous when initial number of females genotyped was low. Genotyping more males was also advantageous for genetic gain, but not to the extent of genotyping more females. Genotyping females also had the advantage of reducing inbreeding when selection of full sibs was not allowed. Inbreeding rates increased when more males were genotyped, due to the opportunity to select full sibs rather than just one male per litter. Progeny testing greatly increased male accuracy but did not result in increased genetic gain due to increased generation interval required to wait on progeny test results. The progeny testing scheme resulted in the lowest rate of inbreeding (Lillehammer et al., 2011). In simulations of both a maternal ( $h^2 = 0.1$  to  $0.2$ ) and a production trait ( $h^2 = 0.3$  to  $0.4$ ), all genomic selection scenarios increased genetic gain compared to conventional BLUP. Genotyping more animals resulted in similar increases in overall genetic gain regardless of whether the animals were male or female. However, the percentage of gain represented by the maternal trait increased as more females were genotyped, while genotyping more males did not increase maternal trait response (Lillehammer et al., 2013). Genomic selection may be especially beneficial for conformation traits, since most are lowly heritable, by increasing their relative genetic gain compared to other, often more highly heritable, traits in the breeding goal (Lillehammer et al., 2013).

Genomic selection was relatively less effective without continued phenotyping, which should be performed as much as economically and biologically possible even after



implementation of genomic selection. A simulated genomic selection scenario in which phenotypes were taken on a small number of relatives produced significantly ( $P < 0.001$ ) reduced annual genetic gain for a high heritability trait ( $h^2 = 0.4$ ) compared to BLUP with phenotypes on all selection candidates. However, the genomic selection scenario resulted in about the same annual genetic gain in the overall breeding goal as traditional BLUP when also considering a lower heritability trait ( $h^2 = 0.2$ ) that was only phenotyped in a small number of relatives in both scenarios (Tribout et al., 2012). For traits with both low and high heritability ( $h^2 = 0.1$  and  $0.4$ , respectively), genomic selection when only siblings were phenotyped was not better than traditional BLUP when all selection candidates were phenotyped; this was particularly because the training population was not updated each generation (Samorè et al., 2015).

Purebred performance is not always a good predictor of descendant crossbred performance due to genetic and environmental differences between nucleus and commercial populations (Dekkers, 2007). Genomic selection may be a solution to this problem as it can be performed without crossbred pedigree information and crossbred phenotypes are not required every generation (Meuwissen et al., 2001). Ibáñez-Escriche et al. (2009) simulated crossbred selection scenarios to assess genomic selection accuracy using a classical model with across-breed SNP effects or a model with breed-specific SNP effects as the linkage disequilibrium structure is different between breeds and can affect SNP effects. Generally, accuracy was greater in breeds that made up a higher proportion of the crossbred (50 vs. 25%). Most of the time, accuracy increased as breeds were more closely related, but the effect tended to be greater in simulations with fewer markers and records. The two models performed similarly in terms of accuracy, with just

a few exceptions. Generally, the breed-specific model was more advantageous when breeds were less related with lower marker density and less probability that QTL were in linkage disequilibrium with markers across populations. A larger training population size was needed for the breed-specific model as more information is needed to estimate more parameters (i.e., separate marker effects for each breed; Ibáñez-Escriche et al., 2009).

Overall economics must be considered before implementation of a genomic selection program as there are costs associated with genotyping. Results from cost-benefit analyses demonstrated that simulated genomic selection schemes would be profitable in a commercial scale breeding program (Lillehammer et al., 2013). A large population is necessary for a return over investment, and genotyping more animals becomes more beneficial as population size increases (Lillehammer et al., 2011). Optimizing the number and ratio of males and females genotyped and use of imputation are potential ways to save money while still getting most of the benefits of genomic selection. Marginal returns from genomic selection were shown to diminish as the proportion of selection candidates genotyped increased. The magnitude of returns and the rate at which they diminished depended on genomic information reliability and, to a lesser extent, ratio of males and females genotyped. However, the specific rate at which diminished marginal returns occur and optimal male to female genotyping ratio will be variable based on trait heritability and phenotype availability (Henryon et al., 2012). Imputation accuracy was high in all genotyping scenarios tested and SNP panel densities, though increased number of individuals with high density genotypes that are more closely related and lesser reduction of SNP panel density resulted in higher imputation accuracy (Cleveland and Hickey, 2013).

Genomic selection could benefit genetic progress in conformation traits. It is especially beneficial for lowly heritable traits. Phenotyping conformation traits is not quick or straightforward. Genomic selection could potentially reduce the need for phenotypes but would not eliminate it. Trade-offs between cost reduction by recording fewer phenotypes and the resulting lowered accuracies would need to be assessed. Genomic selection could also be beneficial for selecting for improved commercial crossbred female conformation in nucleus animals. Genomic selection is likely economically advantageous in a large-scale breeding program, but economic optimization requires consideration of many factors, including number and ratio of each sex genotyped and phenotyped and proper use of lower density SNP panels and imputation.

### **1.7 Overall Conclusion**

Conformation traits are influenced by a variety of factors, including management practices, housing, nutrition, and genetics. As such, a multi-dimensional approach is required for the greatest success in improving these traits. However, further research is required to define the best management, nutritional, and genetic strategies for improving conformation. The first step is developing an objective, reliable, and standardized method for phenotyping conformation to directly compare study results and allow new research to build on previous studies. Heritability of conformation traits must be estimated and genetic correlations between conformation and economically important traits, such as longevity, must be identified to incorporate conformation as an indicator trait in an economic selection index. Genetic correlations between conformation measured at different times of life should also be assessed to determine if conformation at the time of selection is an accurate predictor of conformation later in life. Finally, conformation traits

are highly polygenic, and genomic selection may benefit genetic progress for conformation traits.

## 1.8 References

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## **CHAPTER 2: OBJECTIVE MEASUREMENTS OF SOW CONFORMATION TRAITS ARE RELIABLE BETWEEN EVALUATORS**

### **2.1 Abstract**

Conformation is economically important to the swine industry, but consistent and reliable assessment methods are lacking. An objective measurement system was employed to evaluate 13 conformation traits at 16 time points in sows ( $n = 622$ ) between 112 days of age and weaning of parity 4. Five body size traits—body length (BL), body depth at the shoulder (BDS) and flank (BDF), and height at the shoulder (HS) and flank (HF)—, and five leg and body angles—knee angle (KA), hock angle (HA), front (FP) and rear (RP) pastern angles, and rump slope (RS)—were objectively measured from side profile images of sows. Images from the front view and in front of the rear leg were utilized to objectively measure foot directional positioning (i.e., toed in or out) on the front left (TIOFL), front right (TIOFR), and rear left (TIOR) feet. Using ImageJ software, body size and foot directional position traits were measured by two evaluators, and leg and body angles were measured by three evaluators. Additionally, a single evaluator measured each trait collected at late second gestation twice. Intra-class correlations and 95% confidence intervals between evaluators were computed for each trait at each time point and within evaluator for each trait at late second gestation. Intra-class correlations for ranged from 0.56 to 0.91 for body size traits, 0.34 to 0.81 for leg and body angles, and 0.63 to 0.96 for foot directional position traits. Intraclass correlations between measurements taken by the same evaluator were higher for all traits. Objective measurement of conformation traits is beneficial due to improved consistency over

traditional subjective scoring methods and the ability to capture the full range of trait values.

## **2.2 Introduction**

Feet and leg conformational problems are a major economic and welfare concern in the swine industry. Lameness is a major reason for early culling, which results in lost revenue due to sows not remaining in the herd long enough to cover their development and maintenance costs (Stalder et al., 2003) or reach their peak level of reproductive performance (English et al., 1978, as cited by Friendship et al., 1986). Numerous studies have been conducted to consider approaches to improve conformation through management (Hacker et al., 1994; Jørgensen 2003), nutrition (Calabotta et al., 1982; Barczewski et al., 1990; Jørgensen 1995; Jørgensen and Sorensen, 1998; Knauer et al., 2011), and genetic selection (Serenius et al., 2001; de Sevilla et al., 2009; Fan et al., 2009; Nikkilä et al., 2013; Le et al., 2015). However, definitions of conformation traits and assessment protocols vary widely between studies, rendering comparisons very difficult. A standardized method of conformation trait phenotyping would greatly benefit the research community and swine industry by enabling direct comparison of study results and allowing clearer conclusions to be drawn from the body of literature.

Furthermore, conformation traits have typically been assessed using subjective numerical scales that different observers are often unable to apply consistently (Van Steenbergen, 1989; Main et al., 2000). Using an objective approach would likely improve the reliability of conformation phenotypes and aid in selection and management of more robust replacement females with better conformation and hence improved longevity (Stock et al., 2017). Using digital imaging to measure conformation traits has been shown

to be more repeatable than subjective scoring systems (Stock et al., 2017), but reliability when images are assessed by different evaluators has yet to be determined. The objective of this study was to evaluate objective conformational trait measurement reliability when assessed by multiple evaluators.

## **2.3 Materials and Methods**

### **2.3.1 Animals and Management**

All procedures involving animals were approved by the University of Nebraska Institutional Animal Care and Use Committee protocol number 1859. Sows used in this study ( $n = 622$ ) were developed in five cohorts. The maternal side of the base population was derived from Nebraska Index Line, selected for increased litter size since 1981 (Hsu and Johnson, 2014). Cohorts 1 and 2 had commercial Landrace sires, and cohorts 3 to 5 were sired by commercial Yorkshire boars. Dams of cohorts 3 to 5 were sows from previous cohorts that had achieved four parities. All sows were part of a larger, ongoing project designed for genetic and nutritional sow reproductive longevity studies.

Gilts were weaned at  $20.0 (\pm 1.4)$  days of age and received the same management until the start of the development period, which began at  $112.3 (\pm 4.3)$  days of age, preceding the onset of first estrus. No preselection for conformation traits was performed prior to study initiation. Gilts were allocated to one of three developmental dietary treatments: a standard corn-soybean meal diet (CTRL), an energy-restricted diet via inclusion of 40% soyhulls (RES) but with similar amino acids and other nutrients as CTRL, and a diet with the same metabolizable energy as CTRL but with the same lysine to metabolizable energy ratio as RES (LYS). All diets were formulated to meet the

nutrient requirements of developing gilts. Dietary treatments were fed in three phases from 112 to 225 days of age in cohorts 1 and 2 and in two phases from 112 to 209 days of age in cohorts 3 to 5 to allow earlier first mating in accordance with industry practices. All sows received the same standard gestation and lactation diets for the remainder of the experiment.

During first gestation, gilts were allocated to either group pen or individual stall housing in cohorts 1 and 3 to 5. Due to management constraints at the time, cohort 2 gilts were housed in stalls only. All sows were housed in stalls during each gestation thereafter. Sows remained in production through four parities if they were able to successfully express estrus, conceive, farrow, and wean a litter in each parity. Gilts were eligible for breeding if they had two heat, no serve events and were given 21 days to express estrus for first breeding. After weaning, sows had ten days to return to estrus for breeding. Sows were only culled for reproductive failure, as described earlier, or due to concerns over health and well-being, such as severe illness or lameness.

### **2.3.2 Conformation Trait Data Collection**

Sows were filmed (SJ4000 portable action cameras, SJCAM Limited, Shenzhen Zhencheng Technology Co. Ltd., Shenzhen, China) at day 58.4 ( $\pm 6.7$ ) and 98.9 ( $\pm 5.2$ ) of gestation (G) and 1.6 ( $\pm 1.9$ ) days after weaning each parity (P; hereafter “mid G”, “late G”, and “wean P”, respectively). In first gestation (G1), sows were also filmed at day 30.2 ( $\pm 6.5$ ) of gestation (hereafter “early G1”). Cohorts 2 to 5 were filmed during the developmental phase at 112.3 ( $\pm 4.3$ ) and 206.3 ( $\pm 6.4$ ) days of age, and cohorts 3 to 5 were also filmed at 167.1 ( $\pm 3.4$ ) days of age (hereafter “early dev”, “late dev”, and “mid dev”, respectively). Sows were walked into the filming area, which had front and rear

gates and a wire panel on the side. The filming area measured 50.8 cm by 2.5 m in the gestation barn and 40.6 cm by 1.3 m in the development area. In the gestation barn, the front gate had a feeder attached to help entice the sows to remain properly positioned relative to the cameras and prevent restlessness. During gestation, sows were filmed from a single consistent side, as well as from the front and rear. Front and rear cameras were mounted to the front and rear gates of the filming area, approximately 14 cm and 36.2 cm above the ground, respectively. The side camera was set up on a tripod 40.6 cm off the ground and 0.9 m away from the sow during filming that occurred during development; during gestation, the camera was instead positioned 1.3 m away from the sow to ensure the entire body of larger sows fit within the field of view. Handheld cameras were manually positioned above both the front and rear feet and in front of the rear foot in both development and gestation periods. Some filming views were added and changed in the early stages of the experiment as filming methods were improved and refined. The available data at each time point is summarized in table 2.1.

Still images were captured from each video using VideoPad Video Editor (NCH Software, Canberra, Australia). Images were taken when the sow was in a representative, natural stance with her body square and legs in line with each other. Conformation traits were measured manually using the length and angle tools in ImageJ (National Institute of Health, Bethesda, MD, USA) in a similar procedure to that of Stock et al. (2017). Ten traits were measured from the side view, specifically five body size and five leg and body angle traits (Figure 2.1). Body size traits were body length (BL, distance from the neck to the rump at the longest point), body depth at the shoulder (BDS, torso height just posterior to the front leg near the shoulder joint), body depth at the flank (BDF, torso



Table 2.1. Camera views<sup>1</sup> filmed at each time point<sup>2</sup>

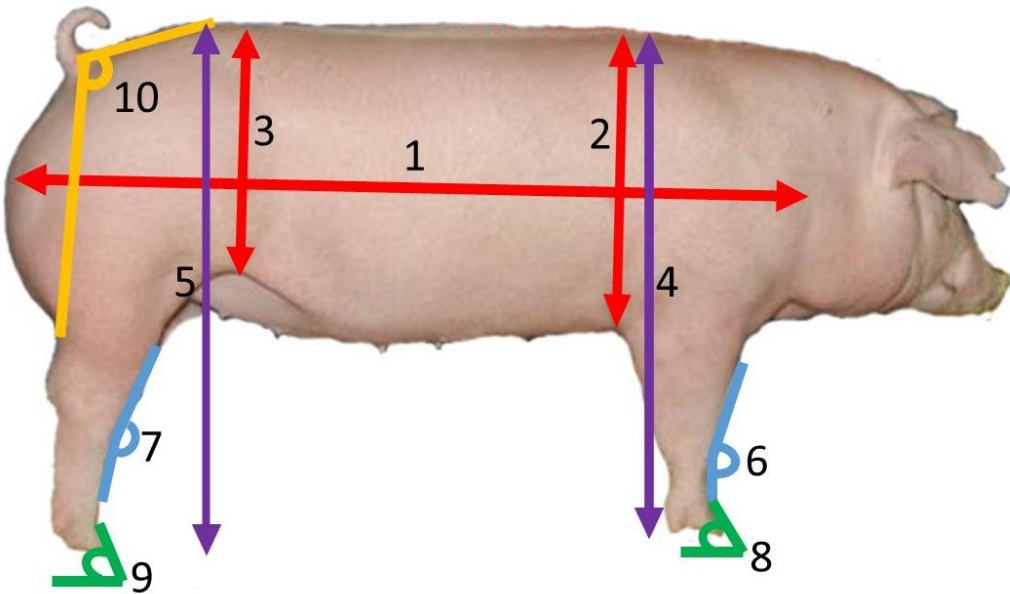
	Cohort 1	Cohort 2	Cohort 3	Cohort 4	Cohort 5
<b>Early Dev</b>		S	S, FT	S, FR, FT	S, FR, FT
<b>Mid Dev</b>			S, FT	S, FR, FT	S, FR, FT
<b>Late Dev</b>		S, FT	S, FT	S, FR, FT	S, FR, FT
<b>Early G1</b>	S, FT	S, F, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Mid G1</b>	S, F, FT	S, F, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Late G1</b>	S, F, FT	S, F, R, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Wean P1</b>	S, F	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Mid G2</b>	S, F, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Late G2</b>	S, F, R, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Wean P2</b>	S, F, R, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Mid G3</b>	S, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Late G3</b>	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Wean P3</b>	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Mid G4</b>	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Late G4</b>	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT
<b>Wean P4</b>	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT	S, F, R, FR, FT

<sup>1</sup>S = side view, F = front view, R = rear view, FR = front view of the rear foot, FT = feet tops

<sup>2</sup>Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

height just anterior to the rear leg to the point of the rump), height at the shoulder (HS, height from the bottom of the front foot to the point of the shoulder), and height at the flank (HF, height from the bottom of the rear foot to the point of the rump). Leg and body angles measured were knee angle (KA, angle following the curve of the anterior side of the front leg with the point at the knee joint), hock angle (HA, angle following the curve of the anterior side of the rear leg with the point at the hock joint), front and rear pastern angle (FP and RP, respectively, angles following the anterior contour from the metacarpophalangeal joint to the interphalangeal joints and straight back near the bottom of the foot), and rump slope (RS, angle from the point of the rump to the center of the

Figure 2.1. Side view conformation traits measured



1 = body length (BL, cm), 2 = body depth at the shoulder (BDS, cm), 3 = body depth at the flank (BDF, cm), 4 = height at the shoulder (HS, cm), 5 = height at the flank (HF, cm), 6 = knee angle (KA, degrees), 7 = hock angle (HA, degrees), 8 = front pastern angle (FP, degrees), 9 = rear pastern angle (RP, degrees), 10 = rump slope (RS, degrees)

tailhead and straight down). Angles assessing foot directional position (i.e., toed in or out) on the front left and front right (TIOFL and TIOFR, respectively) were measured from front view images captured from the camera mounted on the front gate. Pictures captured from the camera held in front of the rear foot were used to measure foot directional position on the rear foot (TIOR; Figure 2.2). These angles began in the center of the toes at the point of divergence, came to a point halfway between the toe tips, and went straight inward. The foot was facing straight forward if the angle was 90 degrees while angles less than 90 degrees indicated “toed out” feet and angles greater than 90 degrees indicated “toed in” feet.

Each conformation trait was independently measured by two to three different evaluators, with the number of evaluators determined by measurement consistency assessed using Pearson correlations and mean differences between sets of measurements

collected by different evaluators and intraclass correlations. Each evaluator was trained by a single facilitator to measure each trait they were assigned via demonstration followed by their supervised evaluation of approximately ten sows. Each evaluator began with a full cohort group at a single time point, and those measurements were reviewed for consistency as compared to the facilitator's measurements via Pearson correlations and mean differences before the evaluator could proceed with more measurements. The same set of evaluators completed measurements at all time points within cohort and trait.

Figure 2.2. Foot directional positioning angle measurement<sup>1</sup>



<sup>1</sup>Angles assessing directional position of foot (i.e., toed in or out) on the front left (TIOFL), front right (TIOFR) and rear left (TIOR) feet, measured in degrees. Angles of 90 degrees indicate the foot is facing straight forward, while angles less than 90 degrees indicate the foot is “toed out” and angles greater than 90 degrees indicate the foot is “toed in”.

### 2.3.3 Statistical analysis

Intraclass correlations (ICC) were calculated for every trait at every time point using R v.4.0.3 (R Core Team, 2020) with the lmer function from the lme4 package (Bates et al., 2015). The linear mixed model included fixed effects of cohort, diet, housing system during first gestation (G1H), cohort by diet interaction, and diet by G1H

interaction. Random effects were animal and evaluator. Effects involving G1H were omitted for time points occurring during the gilt development phase. The ICC value was calculated as the animal variance divided by the total variance. Confidence intervals (CI) were constructed using bootstrapping with the bootMer function in the lme4 package using 10,000 sampling events (iterations). Various numbers of iterations were tested, and 10,000 was found to be sufficient as the same results were consistently produced and were not changed by increasing the number of iterations. The 2.5<sup>th</sup> and 97.5<sup>th</sup> percentiles of the simulated distributions were used to construct 95% CI. Additionally, ICC was calculated for two sets of measurements for all traits at the mid G2 time point taken by the same evaluator using the same procedure, except evaluator was omitted from the model, to compare between and within evaluator consistency. Values of the ICC below 0.5 were considered to indicate poor agreement, between 0.50 and 0.75 to indicate moderate agreement, between 0.75 and 0.90 to indicate good agreement, and above 0.90 to indicate excellent agreement (Koo and Li, 2016).

## **2.4 Results**

Two sets of objective measurements were obtained for body size traits (BL, BDS, BDF, HS, and HF). The ICC values for these traits would be considered moderate to excellent and ranged from 0.56 to 0.91 (Table 2.2). Average ICC values were 0.73, 0.77, 0.79, 0.77, and 0.86 for BL, BDS, BDF, HS, and HF, respectively. Most lower bounds for the 95% CI were in the moderate to good range and remained above 0.5 for all but eight trait and time combinations.

Table 2.2. Intra-class correlations (ICC) between measurements of body size traits<sup>1</sup> assessed by different evaluators and lower and upper bounds of 95% confidence intervals.

Time <sup>2</sup>	BL			BDS			BDF			HS			HF		
	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>
<b>Early Dev</b>	0.85	0.77	0.90	0.71	0.55	0.82	0.82	0.78	0.86	0.69	0.51	0.84	0.90	0.85	0.93
<b>Mid Dev</b>	0.79	0.64	0.87	0.58	0.38	0.72	0.68	0.57	0.75	0.58	0.34	0.79	0.85	0.80	0.89
<b>Late Dev</b>	0.80	0.69	0.87	0.66	0.53	0.75	0.79	0.75	0.83	0.63	0.46	0.76	0.81	0.75	0.85
<b>Early G1</b>	0.84	0.74	0.90	0.82	0.78	0.85	0.87	0.84	0.90	0.79	0.67	0.87	0.89	0.82	0.93
<b>Mid G1</b>	0.82	0.73	0.88	0.84	0.81	0.87	0.86	0.82	0.89	0.84	0.75	0.89	0.88	0.84	0.91
<b>Late G1</b>	0.73	0.57	0.84	0.82	0.79	0.85	0.83	0.80	0.86	0.84	0.75	0.90	0.91	0.85	0.94
<b>Wean P1</b>	0.73	0.57	0.84	0.77	0.73	0.81	0.86	0.83	0.89	0.85	0.77	0.91	0.90	0.86	0.92
<b>Mid G2</b>	0.67	0.48	0.82	0.80	0.77	0.84	0.82	0.74	0.87	0.79	0.71	0.85	0.81	0.67	0.90
<b>Late G2</b>	0.56	0.34	0.78	0.81	0.77	0.85	0.80	0.74	0.85	0.75	0.61	0.85	0.83	0.74	0.89
<b>Wean P2</b>	0.73	0.58	0.84	0.85	0.82	0.88	0.75	0.58	0.87	0.83	0.71	0.90	0.89	0.80	0.94
<b>Mid G3</b>	0.66	0.46	0.84	0.83	0.75	0.89	0.60	0.38	0.81	0.85	0.75	0.91	0.81	0.64	0.92
<b>Late G3</b>	0.71	0.55	0.83	0.80	0.73	0.85	0.68	0.51	0.82	0.81	0.71	0.88	0.83	0.70	0.91
<b>Wean P3</b>	0.74	0.61	0.83	0.73	0.63	0.82	0.84	0.74	0.90	0.76	0.61	0.87	0.90	0.82	0.94
<b>Mid G4</b>	0.71	0.54	0.84	0.77	0.62	0.87	0.80	0.66	0.90	0.78	0.65	0.88	0.86	0.73	0.93
<b>Late G4</b>	0.72	0.57	0.82	0.78	0.64	0.87	0.82	0.73	0.88	0.79	0.66	0.88	0.80	0.67	0.89
<b>Wean P4</b>	0.63	0.43	0.81	0.79	0.68	0.86	0.85	0.77	0.90	0.78	0.61	0.89	0.85	0.75	0.92

<sup>1</sup>BL = body length; BDS = body depth shoulder; BDF = body depth flank; HS = height shoulder; HF = height flank

<sup>2</sup>Time of measurement: Early Dev = near the beginning of the developmental period at 112 days of age, Mid Dev = near the middle of the developmental period at 167 days of age, End Dev = near the end of the developmental period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of fourth parity

<sup>3</sup>Lower bound of the 95% confidence interval

<sup>4</sup>Upper bound of the 95% confidence interval

Table 2.3. Intra-class correlations (ICC) between measurements of side view angle traits<sup>1</sup> assessed by different evaluators and lower and upper bounds of 95% confidence intervals.

Time <sup>2</sup>	KA			HA			FP			RP			RS		
	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>
<b>Early Dev</b>	0.45	0.28	0.63	0.57	0.38	0.75	0.46	0.38	0.53	0.63	0.50	0.74	0.60	0.42	0.76
<b>Mid Dev</b>	0.41	0.25	0.60	0.43	0.26	0.63	0.42	0.33	0.50	0.65	0.53	0.74	0.51	0.32	0.71
<b>Late Dev</b>	0.44	0.28	0.62	0.44	0.27	0.66	0.48	0.41	0.55	0.64	0.56	0.71	0.53	0.37	0.68
<b>Early G1</b>	0.48	0.35	0.59	0.57	0.40	0.71	0.44	0.37	0.52	0.61	0.52	0.67	0.61	0.43	0.77
<b>Mid G1</b>	0.54	0.42	0.64	0.61	0.47	0.72	0.44	0.37	0.52	0.63	0.54	0.70	0.56	0.39	0.71
<b>Late G1</b>	0.59	0.48	0.68	0.62	0.48	0.72	0.48	0.40	0.55	0.67	0.61	0.73	0.54	0.35	0.75
<b>Wean P1</b>	0.59	0.45	0.69	0.55	0.38	0.70	0.39	0.31	0.47	0.53	0.43	0.62	0.52	0.34	0.70
<b>Mid G2</b>	0.54	0.40	0.66	0.42	0.24	0.65	0.49	0.41	0.57	0.62	0.51	0.70	0.66	0.48	0.81
<b>Late G2</b>	0.51	0.36	0.66	0.46	0.27	0.68	0.48	0.41	0.56	0.71	0.67	0.75	0.68	0.51	0.81
<b>Wean P2</b>	0.41	0.25	0.60	0.50	0.33	0.68	0.51	0.43	0.58	0.64	0.56	0.71	0.66	0.50	0.79
<b>Mid G3</b>	0.47	0.31	0.64	0.58	0.41	0.73	0.49	0.42	0.57	0.71	0.67	0.76	0.61	0.44	0.76
<b>Late G3</b>	0.48	0.32	0.65	0.55	0.38	0.71	0.55	0.46	0.62	0.72	0.68	0.77	0.62	0.48	0.74
<b>Wean P3</b>	0.49	0.33	0.65	0.56	0.38	0.74	0.64	0.58	0.70	0.76	0.72	0.80	0.66	0.49	0.80
<b>Mid G4</b>	0.47	0.33	0.61	0.71	0.58	0.81	0.61	0.56	0.68	0.81	0.77	0.85	0.66	0.47	0.83
<b>Late G4</b>	0.48	0.32	0.65	0.71	0.55	0.83	0.66	0.61	0.72	0.77	0.72	0.82	0.71	0.56	0.84
<b>Wean P4</b>	0.34	0.19	0.57	0.38	0.20	0.70	0.64	0.58	0.71	0.74	0.69	0.80	0.54	0.34	0.78

<sup>1</sup>KA = knee angle; HA = hock angle; FP = front pastern angle; RP = rear pastern angle; RS = rump slope

<sup>2</sup>Time of measurement: Early Dev = near the beginning of the developmental period at 112 days of age, Mid Dev = near the middle of the developmental period at 167 days of age, End Dev = near the end of the developmental period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of fourth parity

<sup>3</sup>Lower bound of the 95% confidence interval

<sup>4</sup>Upper bound of the 95% confidence interval

Three sets of objective measurements were obtained for side view angle traits (KA, HA, FP, RP, and RS). Poor to good agreement between evaluators was observed for these traits, with ICC values ranging from 0.34 to 0.81 (Table 2.3). Knee angle, FP, and HA had the lowest ICC values at 0.48, 0.51, and 0.54 on average, respectively, while RS and RP were slightly higher with average ICC values of 0.60 and 0.68, respectively. Most lower bounds of the 95% CI dropped below 0.5 for all traits except RP. Aside from FP, all upper bounds were above 0.6 except KA at early G1 and wean P4.

Two sets of objective measurements were obtained for foot directional position (i.e., toed in or out; TIOFL, TIOFR, TIOR). These foot directional angles had moderate to excellent ICC values, ranging from 0.63 to 0.96 (Table 2.4). Average ICC values were 0.76, 0.83, and 0.94 for TIOFL, TIOFR, and TIOR, respectively. The only lower 95% CI bound to fall below the moderate range was TIOFL at mid G4, while all lower 95% CI bounds for TIOR were within the good or excellent range.

Intra-class correlations between two sets of late G2 objective measurements assessed by the same evaluator were greater than ICC values between different evaluators for all traits (Table 2.5), except the maximum ICC for TIOR, which was equivalent. The range between the lower and upper bounds of the 95% CI decreased when each set of measurements was assessed by the same evaluator, aside from some equivalently narrow ranges for TIOR.

## **2.5 Discussion**

Intra-class correlations are widely used to determine reliability between multiple observers on the same subjects (inter-observer reliability) and one observer on multiple

Table 2.4. Intra-class correlations (ICC) between measurements of foot directional position (i.e., toed in or out) traits<sup>1</sup> assessed by different evaluators and lower and upper bounds of 95% confidence intervals.

<b>Time<sup>2</sup></b>	<b>TIOFL</b>			<b>TIOFR</b>			<b>TIOR</b>		
	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>	ICC	Lower <sup>3</sup>	Upper <sup>4</sup>
<b>Early G1</b>	0.86	0.82	0.89	0.83	0.73	0.88	0.96	0.95	0.97
<b>Mid G1</b>	0.80	0.65	0.88	0.82	0.77	0.87	0.96	0.95	0.97
<b>Late G1</b>	0.79	0.72	0.84	0.83	0.80	0.86	0.96	0.92	0.97
<b>Wean P1</b>	0.78	0.66	0.86	0.88	0.85	0.90	0.92	0.84	0.97
<b>Mid G2</b>	0.73	0.52	0.87	0.86	0.76	0.91	0.95	0.92	0.97
<b>Late G2</b>	0.79	0.58	0.91	0.89	0.86	0.92	0.91	0.86	0.94
<b>Wean P2</b>	0.77	0.57	0.90	0.83	0.70	0.90	0.96	0.94	0.97
<b>Mid G3</b>	0.78	0.72	0.83	0.73	0.64	0.80	0.94	0.91	0.96
<b>Late G3</b>	0.73	0.51	0.87	0.86	0.76	0.91	0.93	0.89	0.95
<b>Wean P3</b>	0.77	0.53	0.92	0.81	0.68	0.89	0.95	0.94	0.97
<b>Mid G4</b>	0.63	0.47	0.76	0.68	0.62	0.75	0.92	0.87	0.95
<b>Late G4</b>	0.75	0.50	0.91	0.87	0.83	0.91	0.95	0.93	0.96
<b>Wean P4</b>	0.74	0.51	0.90	0.86	0.79	0.91	0.95	0.93	0.97

<sup>1</sup>TIOFL = front left foot directional position (i.e., toed in or out); TIOFR = front right foot directional position (i.e., toed in or out); TIOR = rear left foot directional position (i.e., toed in or out)

<sup>2</sup>Time of measurement: Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of fourth parity

<sup>3</sup>Lower bound of the 95% confidence interval

<sup>4</sup>Upper bound of the 95% confidence interval

subjects (intra-observer reliability). The ICC account for both the correlation between measurements and agreement between observers, providing a better assessment of reliability than either factor alone (Koo and Li, 2016). The intra-observer reliability for body size traits were, on average, moderate to good across times. However, when considering the corresponding 95% confidence intervals, those correlations were in the poor to good range. The ICC for height at the flank was the exception in which the confidence intervals fell in the moderate to excellent range, and the ICC values were



Table 2.5. Intra-class correlations (ICC) between measurements assessed by the same evaluator at day 99 of second gestation and lower and upper bounds of 95% confidence intervals.

<b>Trait<sup>1</sup></b>	<b>ICC</b>	<b>Lower<sup>2</sup></b>	<b>Upper<sup>3</sup></b>
<b>BL</b>	0.93	0.91	0.94
<b>BDS</b>	0.89	0.88	0.92
<b>BDF</b>	0.91	0.90	0.93
<b>HS</b>	0.93	0.92	0.95
<b>HF</b>	0.96	0.96	0.97
<b>KA</b>	0.85	0.82	0.88
<b>HA</b>	0.81	0.78	0.85
<b>FP</b>	0.76	0.72	0.81
<b>RP</b>	0.90	0.89	0.92
<b>RS</b>	0.92	0.91	0.94
<b>TIOFL</b>	0.94	0.93	0.95
<b>TIOFR</b>	0.94	0.93	0.96
<b>TIOR</b>	0.96	0.95	0.97

<sup>1</sup>BL = body length, BDS = body depth at the shoulder, BDF = body depth at the flank, HS = height at the shoulder, HF = height at the flank, KA = knee angle, HA = hock angle, FP = front pastern angle, RP = rear pastern angle, RS = rump slope, TIOFL = front left foot directional position (i.e., toed in or out), TIOFR = front right foot directional position (i.e., toed in or out), TIOR = rear left foot directional position (i.e., toed in or out)

<sup>2</sup>Lower bound of the 95% confidence interval

<sup>3</sup>Upper bound of the 95% confidence interval

good to excellent. Measures of side view angles had lower ICC values on average, with poor to moderate inter-observer reliabilities. The exception was RP with moderate to good ICC across times. When considering the 95% CI, some of the upper values for RS and HA exceeded the threshold for the good range. Angles associated with foot directional position (i.e., toed in or out) had high ICC, with 95% CI in the good to excellent range for the rear foot and moderate to excellent range for front feet.

There are a few reasons why leg and body angles may have been more difficult to measure consistently when compared to body size and foot directional position traits. First, angles require the identification of three precise anatomical locations, whereas length measurements only require two. Furthermore, the magnitude of measurement change because of small deviations in the position of the anatomical locations or points

defining angles is greater than small deviations in the start and end positions of a length line. Consistently identifying the inflection points defining leg and body angles is particularly important. Finally, the side view camera was positioned far enough away to capture the entire side profile of the sow. The distance between the camera and anatomical locations being measured on the side was therefore greater than for foot directional position traits.

The improved reliability of TIOR compared to TIOFL and TIOFR may be due to camera positioning; the camera was positioned directly in front of the rear foot while the front feet shared a camera positioned between them. Likewise, all side view traits were measured from images captured by a single camera placed near the center of the body. Positioning cameras directly perpendicular to each leg may result in increased reliability of leg angle measurements. A directly centered and closer view of the specific angle to be measured may allow more precise identification of specific anatomical features, resulting in greater reliability between evaluators, as observed with TIOR compared to TIOFL and TIOFR.

Sets of objective measurements taken by the same evaluator were more consistent and reliable than sets of measurements taken by different evaluators. While this is generally expected, it may indicate that reliability could benefit from more extensive evaluator training. The supervised evaluation portion of the training could have been more extensive and repeated at regular intervals. Reliability should also be improved by employing an automated computer system to capture measurements from images. Modern technology, such as deep learning and neural networks, could be utilized to train the computer system to locate specific anatomical features and measure the conformation

traits with greater accuracy and precision than humans. Furthermore, automation would be necessary to make this conformation trait evaluation system practical for use in industry from a labor standpoint.

Numerous studies have evaluated conformation traits in pigs, and most used a subjective scale. However, the specific trait definitions and scale have varied widely among studies, making them difficult to compare and to draw conclusions. Trait definitions have been as broad as “overall type” (López-Serrano et al., 2000) and “overall leg action” (Serenius et al., 2001; Serenius et al., 2004; Fan et al., 2011; Nikkilä et al., 2013). Conversely, other studies have focused on a specific aspect of conformation or taken it a step further to specific structural defects, sometimes with multiple traits assessing one joint. For example, pastern angles have been evaluated as “pastern posture” (Fan et al., 2011; Nikkilä et al., 2013), “weak pastern/plantigradism/down at pasterns” (Hacker et al., 1994; Jørgensen and Sorensen, 1998; de Sevilla et al., 2009) and “straight pastern/upright pastern/up on toes” (Hacker et al., 1994; Serenius et al., 2001; Jørgensen 2003; de Sevilla et al., 2009), or considered as part of “leg posture” (Nikkilä et al., 2013) or “upright legs” (Fan et al., 2011) and “weak legs” (Fan et al., 2011).

Objective conformation trait measurements, as described in the present study, could avoid such ambiguity. A standardized phenotyping system is paramount to advancing research designed to improve conformation in swine. Objectively measured knee, hock, and pastern angles were shown to be repeatable between multiple images of the same animal, including images of both left and right side profiles (Stock et al., 2017). Furthermore, the present study demonstrated that several conformation traits could be repeatability assessed by different evaluators. Reliability of leg angles were found to be

0.40 to 0.54 when evaluated with a subjective 19-point scale (Van Steenbergen, 1989) while on average 0.48 to 0.68 when objectively measured by multiple evaluators on the same image in the present study. When leg angles were measured on multiple images of the same sow by the same evaluator, Stock et al. (2017) reported increased reliabilities of 0.63 to 0.82, with even higher values achieved by using the same image in the current study (0.76 to 0.90).

Additionally, cameras can be positioned in specific and consistent locations relative to the pig. Subjective scores are assessed from the vantage point of the human evaluator, which is often inconsistent as the position of the evaluator relative to the pig likely differs between evaluators, studies, and pigs. Differences in height between evaluators results in viewing the pig from a slightly different perspective, which could lead to differences in assessment. Objective measurements also facilitate capture of the full phenotypic range of trait values, whereas a subjective scoring system with just a few categories does not fully encompass all variation and decreases precision by grouping trait values together, sometimes without regard to the natural variance within the trait. Even when the number of categories is small, some categories are seldom used (Serenius and Stalder, 2007; Guo et al., 2009; Nikkilä et al., 2013). An additional strength of the present study is that gilts were not preselected for conformation which is often the case at a commercial farm where gilts are purchased from a genetic supplier.

## **2.6 Conclusions**

Measurement reliability when utilizing an objective conformation trait measurement system was high for body size traits and angles assessing foot directional position (i.e., toed in or out). For leg angles and rump slope, measurement reliability was

high between multiple measurements assessed by the same evaluator but lower between different evaluators. Objective assessment of conformation traits offers several advantages over subjective scoring methods, including capturing the full range of trait values, a consistent vantage point for evaluation, and improved reliability. An objective evaluation system is necessary to standardize conformation evaluation methods and allow comparison between studies. Future work focused on automation of conformation trait assessment will further improve reliability and efficiency of conformation trait data collection.

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## **CHAPTER 3: OBJECTIVELY MEASURED CONFORMATION TRAITS AND SOW PERFORMANCE ARE INFLUENCED BY DEVELOPMENTAL DIET AND GESTATION HOUSING SYSTEM**

### **3.1 Abstract**

Conformation issues and lameness are major reasons for reduced longevity in sow herds and can be influenced by dietary and housing strategies. Therefore, the effects of dietary energy and lysine content during gilt development and pen or stall housing system during first gestation were assessed. The traits considered were sow reproductive longevity, reproductive performance, objectively measured conformation traits, and foot lesions. Sows were developed in 5 cohorts and fed 1 of 3 developmental diets from 112 to 215 days of age: a standard corn-soybean meal diet (CTRL), an energy restricted diet (40% inclusion of soyhulls; RES), or a diet containing standard energy and supplemental lysine (LYS). They then were allocated to either a group pen or stall during first gestation (G). Conformation traits, including body length and depth, height, knee, hock, and pastern angles, rump slope, and foot directional position angles (toed in or out), were objectively measured from video recordings. Data were collected at 16 time points between 112 days of age and weaning of parity (P) 4 by 2 to 3 evaluators. Three foot lesion types were scored at the same time points. Dietary energy level during gilt development had significant effects on sow feed intake, BW loss, and backfat loss during lactation and litter weaning weight at P1 ( $P < 0.05$ ). In P1, sows fed the RES developmental diet consumed more feed and lost less BW and backfat when compared to sows fed the CTRL and LYS diets; they also weaned heavier litters when compared to gilts fed the CTRL diet. Reproductive longevity was not affected by diet or gestation

housing ( $P > 0.1$ ). Dietary energy level during gilt development influenced all body size traits and knee and hock angles at early, mid, and late G1 ( $P < 0.05$ ). Sows fed the RES diet had smaller body size and straighter knee and hock angles compared to sows fed the CTRL and LYS diets. Gestation housing system affected rump slope and rear pastern at early, mid, and late G1 and front pastern at mid and late G1 ( $P < 0.05$ ); sows housed in pens had steeper rumps and pasterns. The front foot of sows housed in pens had greater toed out angles when compared to sows housed in stalls from early G1 to late G2 ( $P < 0.05$ ). All foot lesion scores were more severe in sows housed in pens throughout G1 ( $P < 0.05$ ). Conformation differences developed quickly after treatment application but also diminished rapidly once treatments were no longer imposed.

### **3.2 Introduction**

Lameness and feet and leg conformational problems are major economic and welfare concerns in the swine industry and represent the second most common reason for early culling in the United States, Mexico, and China (Mote et al., 2008; Segura-Correa et al., 2011; Zhao et al., 2015). Sows must remain in the herd through three parities to cover development and maintenance costs and become profitable (Stalder et al., 2003; Mote et al., 2008). As the industry transitions from individual stall housing to group pen housing during gestation, sow conformation is becoming even more important. Sows are being required to walk to access feed and water and maneuver around other sows in the pen, providing more opportunities to become injured and for feet and leg conformational problems to manifest into lameness. The same is true for growing pigs, which are raised in group pens from weaning to market. Prevalence of lameness has been reported as 8.8 percent (Heinonen et al., 2006) and 9.7 percent (2.4 to 23.1% at individual farms; Pluym

et al., 2011) in group housed sows and 19.7 percent in finishing pigs (KilBride et al., 2009) raised indoors. A higher prevalence of lameness in group-housed sows compared to stall-housed sows has been reported (Calderón Díaz et al., 2014). Lameness causes reduced feed intake in sows (Cornou et al., 2008) and growing pigs (Munsterhjelm et al., 2015) and profit losses in the form of treatment cost, reduced production, and death or euthanasia in severe cases.

Furthermore, caloric restriction without limiting other essential nutrients has been shown to improve longevity in rodents (Merry and Holehan, 1979; McShane and Wise, 1996), and could favorably impact sow reproductive longevity by slowing growth rate and improving feet and leg conformation traits. Caloric restriction prior to breeding has also been associated with improved reproductive performance in rodents. Mice fed energy restricted diets for 11 weeks prior to breeding (and the control diet starting at 10 days prior to breeding) had increased fertility, litter size, and litter weight at both birth and weaning; conversely, mice fed high fat diets prior to breeding had decreased fertility, litter size, and litter weight at both birth and weaning compared to controls (Johnston, 2006). The objectives of this study were to evaluate the effects of dietary energy and lysine content during gilt development and gestation housing system during first gestation on reproductive performance and longevity, objectively measured conformation traits, and foot lesions.

### **3.3 Materials and Methods**

#### **3.3.1 Developmental Period**

All procedures involving animals were approved by the University of Nebraska Institutional Animal Care and Use Committee protocol number 1859. Sows used in this study ( $n = 494$ ) were described in chapter 2 and developed in four cohorts. Gilts were weaned at  $20.0 (\pm 1.4)$  days of age and received the same management until the start of the development period, which began at  $112.3 (\pm 4.3)$  days of age, preceding the onset of first estrus. Prior to nursery exit at approximately 61 days of age, 128 gilts with average to good weaning weight and similar age were selected and randomly allocated within sire and litter to one of 16 pens in two rooms (eight pens/room) and one of three dietary treatments such that full and half siblings were spread across treatments and pens as evenly as possible. Pen floors were 60% solid and 40% slats with dimensions of 4.9 by 1.8 m. Each pen held eight gilts for a stocking density of  $1.1 \text{ m}^2$  per gilt. Slats were 20.3 cm wide with 2.5 cm gaps. Dietary treatments (Table 3.1) were a standard corn-soybean meal diet (CTRL), an energy restricted diet via inclusion of 40% soyhulls (RES) with similar amino acids and other nutrients as CTRL, and a diet with the same metabolizable energy as CTRL and same lysine to metabolizable energy ratio as RES (LYS). The dietary treatments were fed in three phases from 112 to 225 days of age in cohorts 1 and 2 and two phases from 112 to 209 days of age in cohorts 3 to 5 to mimic standard industry practices in which breeding commences at 210 days of age. Diets were designed to test the effects of energy intake on sow longevity and performance and whether those effects were mediated by the lysine to metabolizable energy ratio.

### **3.3.2 Sow Management**

Upon completion of the development period, all sows received the same standard gestation and lactation diets for the remainder of the experiment. Gilts were randomly

Table 3.1. Formulation and calculated composition (as-fed basis) of developmental dietary treatments, control (CTRL), energy restricted (RES), and same energy as CTRL and same Lys:ME as RES (LYS)

Contents	Phase 1			Phase 2			Phase 3		
	CTRL	RES	LYS	CTRL	RES	LYS	CTRL	RES	LYS
<b>Corn</b>	72.52	39.6	70.38	76.32	43.17	74.66	80.13	47.16	78.6
<b>Soybean Meal</b>	21.53	17.78	23.35	17.66	14.13	19	13.79	10.05	15
<b>Soyhulls</b>	0	40	0	0	40	0	0	40	0
<b>Tallow</b>	3	0	3	3	0	3	3	0	3
<b>Dicalcium phosphate</b>	1.37	1.72	1.37	1.46	1.8	1.46	1.54	1.89	1.54
<b>Limestone</b>	0.68	0	0.68	0.66	0	0.66	0.64	0	0.64
<b>Salt</b>	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
<b>Trace Mineral Premix</b>	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
<b>Vitamin Premix</b>	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
<b>L-Lysine-HCL</b>	0	0	0.15	0	0	0.15	0	0	0.15
<b>DL-Methionine</b>	0	0	0.05	0	0	0.05	0	0	0.05
<b>L-Threonine</b>	0	0	0.09	0	0	0.09	0	0	0.09
<b>L-Tryptophan</b>	0	0	0.03	0	0	0.03	0	0	0.03
<b>Calculated Composition<sup>1</sup></b>									
<b>ME, kcal/kg</b>	3406	2705	3408	3408	2706	3410	3410	2707	3412
<b>CP, %</b>	16.25	15.86	17.21	14.72	14.41	15.48	13.18	12.79	13.9
<b>Lysine, SID %</b>	0.7	0.69	0.86	0.61	0.61	0.76	0.51	0.51	0.66
<b>Methionine, SID %</b>	0.24	0.2	0.29	0.22	0.19	0.27	0.2	0.17	0.26
<b>Threonine, SID %</b>	0.5	0.46	0.61	0.44	0.41	0.55	0.39	0.36	0.5
<b>Tryptophan, SID %</b>	0.16	0.15	0.2	0.14	0.13	0.18	0.12	0.11	0.16
<b>Calcium, %</b>	0.67	0.71	0.68	0.67	0.72	0.68	0.67	0.73	0.68
<b>Phosphorus, STTD %</b>	0.35	0.37	0.35	0.35	0.38	0.35	0.35	0.38	0.36

<sup>1</sup>ME = metabolizable energy, CP = crude protein, SID = standard ileal digestible, STTD = standard total tract digestible

allocated to group pen or individual stall housing, where they remained until moving to farrowing stalls at day 109.0 ( $\pm$  2.7) of gestation. Gilts allocated to pen gestation remained with previous pen-mates to reduce fighting due to socialization that occurs when pigs are mixed. Pens were 4.6 by 1.8 m with 60% solid and 40% slats. Slats were 20.3 cm wide with 3.8 cm gaps. Five gilts were housed in each pen in cohort 1 for a stocking density of 1.7 m<sup>2</sup> per gilt; due to management concerns that arose with cohort 1, cohorts 3 to 5 had a stocking density of 2.1 m<sup>2</sup> per gilt with four gilts per pen. All gilts were housed in stalls in cohort 2 and were, therefore, excluded from this study. Stalls had solid floor on the front 50% and slatted floor on the back 50% and were 2.1 m by 48.3 cm, providing 1.0 m<sup>2</sup> of usable space per gilt. All sows were housed in stalls in gestations 2 to 4. In later gestations, sows were housed in stalls that provided 1.3 m<sup>2</sup> per sow with solid floor in the front and slatted floor in the rear. Farrowing crates had cast iron flooring and provided 1.1 m<sup>2</sup> of space for sows to stand with an additional 1.7 m<sup>2</sup> of creep space, which included additional space for the sow to lay down and piglet space.

Gilts were given one opportunity to express estrus and conceive during an initial 21-day breeding period following gilt development where they had two or more heat, no-service events. All females that did not successfully express estrus, conceive, farrow, and wean a litter were removed. Any sow that did not return to estrus and successfully breed within ten days after weaning was also removed. Aside from reproductive failure, culling was only performed when necessary for animal welfare reasons, including sickness and severe injury or lameness. Sows remained in production through four parities if they met the above culling criteria. Culling dates and reasons were recorded.

Sows were weighed and backfat thickness was measured at the last rib with real-time ultrasonics at the end of development ( $212.9 \pm 8.2$  days of age), before farrowing ( $109.0 \pm 2.7$  days of gestation), and at weaning ( $20.2 \pm 1.6$  days after farrowing). Either an Aloka 500V real-time ultrasound instrument equipped with a 3.5-MHz, 17-cm linear transducer (Corometrics Medical System, Inc., Wallingford, CT) or an ExaGo real-time ultrasound equipped with an ASP 13-cm linear transducer (Echo Control Medical, Angoulême, Poitou-Charentes, France) was used. For each litter, total number of piglets born (TNB), number of piglets born alive (NBA), number of stillborn piglets (SB), and number of mummified piglets (MUM) were recorded. Piglets were processed the morning after farrowing and weighed. The birth weight of all fully formed piglets in the litter were summed to obtain total litter birth weight (TBW). All cross-fostering events were documented to obtain number of piglets nursed (NN) and number of piglets weaned (NW), allowing for the calculation of preweaning mortality (PWM). Piglets were individually weighed at weaning, and weights were summed to determine total litter weaning weight (TWW) which was adjusted to a piglet age at weaning of 21 days (AdjTWW) using the National Swine Improvement Federation adjustment formula (<https://www.swineimprovementfederation.com/>). Sows had *ad libitum* access to mash diet that met or exceeded NRC (2012) requirements for lactating sows. Feed intake was recorded during lactation, and total feed intake was divided by the number of days lactating to calculate the average daily lactation feed intake (LFI). Changes in sow BW (LWL) and backfat thickness (LBFL) during the lactation period were calculated, with TBW subtracted from pre-farrowing BW to account for the litter weight.

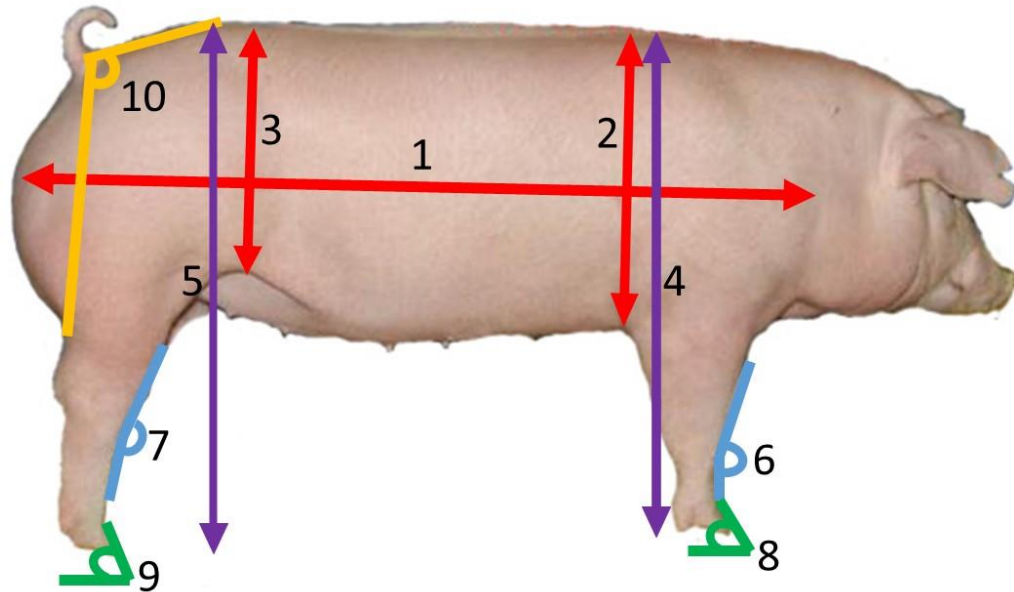
The sum of TNB and NBA for each parity (P) through P4 was calculated to obtain lifetime litter size traits (LT-TNB and LT-NBA, respectively). The number of parities achieved by each sow in their lifetime (LTNP) was recorded up to four parities. Lifespan (LS) was calculated as the number of days between culling date and birth date, while life on test (LOT) was calculated as the number of days between culling date and the development period starting date. Length of productive life (LPL) was calculated as the number of days between culling date and date of first mating. The last date of trial, defined as the date when the last sows in the cohort weaned P4, was used in place of culling date for sows that weaned P4 and completed the trial in LS and LOT as all sows in the cohort began LOT on the same day and birth date was unrelated to P4 wean date. The individual sow's P4 wean date was instead used in place of culling date for LPL as sows that weaned P4 earlier likely had an earlier first mating, though differences in non-productive days also influenced when sows weaned P4.

### **3.3.3 Conformation Trait Data Collection**

Conformation traits were obtained as described in chapter 2. Ten conformation traits were objectively measured from the side view (Figure 3.1), body length (BL), body depth at the shoulder (BDS) and flank (BDF), height at the shoulder (HS) and flank (HF), knee angle (KA), hock angle (HA), front and rear pastern angles (FP and RP, respectively), and rump slope (RS). Foot directional positioning (i.e., toed in or out; Figure 3.2) was measured on the front and rear feet (TIOF and TIOR, respectively) on a single consistent side. Side view traits were collected at 16 time points, 112.3 ( $\pm 4.3$ ), 167.1 ( $\pm 3.4$ ), and 206.3 ( $\pm 6.4$ ) days of age (hereafter “early dev”, “mid dev”, “late dev”), day 30.2 ( $\pm 6.5$ ) of first gestation (hereafter “early G1”), day 58.4 ( $\pm 6.7$ ) and 98.9



Figure 3.1. Side view conformation traits measured



1 = body length (BL, cm), 2 = body depth at the shoulder (BDS, cm), 3 = body depth at the flank (BDF, cm), 4 = height at the shoulder (HS, cm), 5 = height at the flank (HF, cm), 6 = knee angle (KA, degrees), 7 = hock angle (HA, degrees), 8 = front pastern angle (FP, degrees), 9 = rear pastern angle (RP, degrees), 10 = rump slope (RS, degrees)

( $\pm 5.2$ ) of each gestation (hereafter “mid G”, “late G”), and 1.6 ( $\pm 1.9$ ) days after weaning each parity (hereafter “wean P”). Foot directional position (i.e., toed in or out) traits were collected starting with early G1.

Three types of foot lesions were scored by a single evaluator on all feet in cohorts 3 to 5 at all time points described above starting with late dev. Feet were scored for heel overgrowth and erosion (HOE), heel-sole cracks (HSC), and white line cracks (WL) using the FeetFirst® Lesion Scoring Guide (Zinpro Corporation, Eden Prairie, MN) on a 0 to 3 scale for no lesion, mild lesion, moderate lesion, and severe lesion, respectively. The scores from each foot were summed to create a total score from 0 to 12 for HOE, HSC, and WL. Scores of all lesion types on the front feet, rear feet, and all feet were also summed.

Figure 3.2. Foot directional positioning (i.e., toed in or out) angle measurement<sup>1</sup>



<sup>1</sup>Angles assessing directional position of foot (i.e., toed in or out) on the front (TIOF) and rear (TIOR) left feet, measured in degrees. Angles of 90 degrees indicate the foot is facing straight forward, while angles less than 90 degrees indicate the foot is “toed out” and angles greater than 90 degrees indicate the foot is “toed in”.

### 3.3.4 Statistical Analysis

Linear mixed models were constructed using the lmer function from the lme4 package (Bates et al., 2015) in R v.4.0.3 (R Core Team, 2020) to test the effects of developmental diet and housing system during first gestation (G1H) on reproductive longevity, production, and conformation traits and on foot lesions. The data set included 494 animals for conformation trait analysis, 315 animals for foot lesions analysis, and 489 for reproductive longevity and production trait analysis. Models for each trait included fixed effects of cohort, diet, G1H, and all 2- and 3-way interactions. Models for conformation traits included random effects of animal and evaluator while models for reproductive longevity, production traits, and foot lesions included sire as a random effect. Additional covariates were required to explain considerable sources of variation for some production traits; NN was included in models for NW, TNB was included in models for TBW, and NW was included in models for AdjTWW. Including sire in the

model fitted for some production traits resulted in a singularity. In these cases, the sire effect was removed, and the model was implemented with the `lm` function. Models were constructed for each time point separately through wean P2 or until diet and G1H effects became insignificant. The `emmeans` package (Lenth, 2021) and function was used to calculate least squares means (LSM) and perform pairwise comparisons between treatments using the Tukey adjustment for multiple testing (Tukey, 1949) to further explore significant effects.

Reproductive longevity and lifetime litter size traits were also analyzed via survival analysis using a Cox proportional hazards model (Cox, 1972) with the `coxme` package and function (Therneau, 2020) in R v.4.0.3 (R Core Team, 2020) to account for the non-normal distribution of longevity traits caused by mandatory culling at P4. Sows that weaned P4 were considered to have censored records as our experimental protocol did not allow them the opportunity to express their full potential for reproductive longevity traits. Cohort, diet, G1H, and all 2- and 3-way interactions were fixed effects and sire was a random effect.

### **3.4 Results**

#### **3.4.1 Effects of Diet and Gestation Housing System on Reproductive Longevity and Production**

Of the 489 gilts that began the experiment, 126, 68, 49, 46, and 200 sows had LTNP of 0, 1, 2, 3, and 4, respectively. There were no effects of diet, G1H, or cohort on any reproductive longevity trait or lifetime litter size trait detected from the fit of linear or Cox proportional hazards models ( $P > 0.1$ ). Energy restriction during development

resulted in decreased BW and backfat at the end of development and just prior to P1 farrowing ( $P < 0.05$ ). Gilts fed the RES developmental diet weighed  $21.1 \pm 1.2$  kg less with  $0.9 \pm 0.05$  cm less backfat compared to gilts fed the CTRL diet and weighed  $19.0 \pm 1.2$  kg less with  $0.8 \pm 0.05$  cm less backfat compared to gilts fed the LYS diet at the end of development (data not shown). Prior to farrowing P1, gilts fed the RES developmental diet weighed  $17.3 \pm 1.8$  kg less with  $0.5 \pm 0.04$  cm less backfat when compared to gilts fed the CTRL developmental diet and weighed  $14.3 \pm 1.8$  kg less with  $0.4 \pm 0.04$  cm less backfat when compared to gilts fed the LYS developmental diet. Dietary induced differences in BW and backfat persisted until P2 weaning and prior to farrowing P3, respectively. Prior to P2 farrowing, sows fed the RES developmental diet had  $6.9 \pm 2.2$  kg less BW than sows fed the CTRL developmental diet and  $5.6 \pm 2.3$  kg less BW than sows fed the LYS developmental diet. Additionally, sows fed the RES developmental diet had  $0.1 \pm 0.05$  cm less backfat compared to sows fed the CTRL diet. Gestation housing system also influenced BW and backfat prior to farrowing P1; gilts housed in pens were  $5.3 \pm 1.5$  kg lighter and had  $0.1 \pm 0.04$  cm more backfat than gilts housed in stalls. The interaction between diet and G1H prior to P1 farrowing ( $P < 0.05$ ) demonstrates that BW differences between pens and stalls were driven by gilts fed the RES developmental diet.

Developmental diet and G1H were influential for some production traits.

Lactation feed intake was affected by developmental dietary treatment in both P1 and P2 ( $P < 0.05$ ) while LWL and LBFL were influenced by developmental dietary treatment in P1 ( $P < 0.01$ ; Table 3.2). In P1 lactation, sows fed the RES developmental diet consumed  $0.6 \pm 0.1$  and  $0.7 \pm 0.1$  kg more feed per day when compared to sows fed the CTRL and

Table 3.2 Effects<sup>1</sup> of developmental diet<sup>2</sup> on production traits

<b>Trait<sup>3</sup></b>	<b>CTRL</b>	<b>RES</b>	<b>LYS</b>
<b>P1 LFI (kg)</b>	4.22 <sup>a</sup>	4.85 <sup>b</sup>	4.13 <sup>a</sup>
<b>P2 LFI (kg)</b>	5.54 <sup>a</sup>	5.87 <sup>b</sup>	5.50 <sup>a</sup>
<b>P1 LWL (kg)</b>	-20.03 <sup>a</sup>	-14.71 <sup>b</sup>	-22.38 <sup>a</sup>
<b>P1 LBFL (cm)</b>	-0.51 <sup>a</sup>	-0.34 <sup>b</sup>	-0.49 <sup>a</sup>
<b>P1 NBA (piglets)</b>	14.09 <sup>ab</sup>	14.71 <sup>a</sup>	13.61 <sup>b</sup>
<b>P1 AdjTWW (kg)</b>	64.81 <sup>a</sup>	67.31 <sup>b</sup>	65.79 <sup>ab</sup>

<sup>1</sup>Different superscripts differ ( $P < 0.05$ ). Only traits with dietary treatment effects ( $P < 0.05$ ) are included.

<sup>2</sup>Diets fed during the developmental period from 112 to 215 days of age. CTRL = control corn-soybean meal diet, RES = energy restricted via inclusion of 40% soyhulls, LYS = same metabolizable energy as CTRL and lysine to metabolizable energy ratio as RES, resulting in increased lysine.

<sup>3</sup>P1 = parity 1, P2 = parity 2, LFI = feed intake during lactation, LWL = bodyweight loss during lactation, LBFL = backfat loss during lactation, NBA = number of piglets born alive, AdjTWW = total litter weaning weight adjusted for age at weaning

LYS developmental diets, respectively, while sows fed the CTRL and LYS diets lost  $5.3 \pm 1.7$  and  $7.7 \pm 1.7$  kg more BW, respectively, and  $0.2 \pm 0.04$  cm more backfat than sows fed the RES developmental diet. In P2 lactation, sows fed the RES developmental diet ate  $0.3 \pm 0.1$  and  $0.4 \pm 0.1$  kg more per day than sows fed the CTRL and LYS developmental diets, respectively. Housing system during first gestation impacted LFI and LWL in P1 and P2 and LBFL in P1 ( $P < 0.05$ ; Table 3.3). Sows housed in pens consumed  $0.2 \pm 0.1$  and  $0.3 \pm 0.1$  kg more feed per day in P1 and P2 lactation, respectively, when compared to sows housed in stalls. Sows housed in stalls lost  $3.2 \pm 1.4$  and  $2.9 \pm 1.5$  kg more BW when compared to sows housed in pens during P1 and P2 lactation, respectively. Sows housed in pens lost  $0.1 \pm 0.03$  cm more back fat during P1 lactation when compared to sows housed in stalls ( $P < 0.01$ ). Interactions between G1H and cohort for P1 LFI and P1 and P2 LWL ( $P < 0.05$ ) were present. Diet and G1H did not influence LFI or LWL in P3.

Table 3.3 Effects<sup>1</sup> of first gestation housing on production traits

<b>Trait<sup>2</sup></b>	<b>Pen</b>	<b>Stall</b>
<b>P1 LFI (kg)</b>	4.51 <sup>a</sup>	4.29 <sup>b</sup>
<b>P2 LFI (kg)</b>	5.81 <sup>a</sup>	5.47 <sup>b</sup>
<b>P1 LWL (kg)</b>	-17.50 <sup>a</sup>	-20.60 <sup>b</sup>
<b>P2 LWL (kg)</b>	-12.80 <sup>a</sup>	-15.80 <sup>b</sup>
<b>P1 LBFL (cm)</b>	-0.50 <sup>a</sup>	-0.40 <sup>b</sup>
<b>P1 NW (piglets)</b>	11.43 <sup>a</sup>	11.91 <sup>b</sup>
<b>P2 PWM (%)</b>	0.21 <sup>a</sup>	0.17 <sup>b</sup>

<sup>1</sup>Different superscripts differ ( $P < 0.05$ ). Only traits with first gestation housing treatment effects ( $P < 0.05$ ) are included.

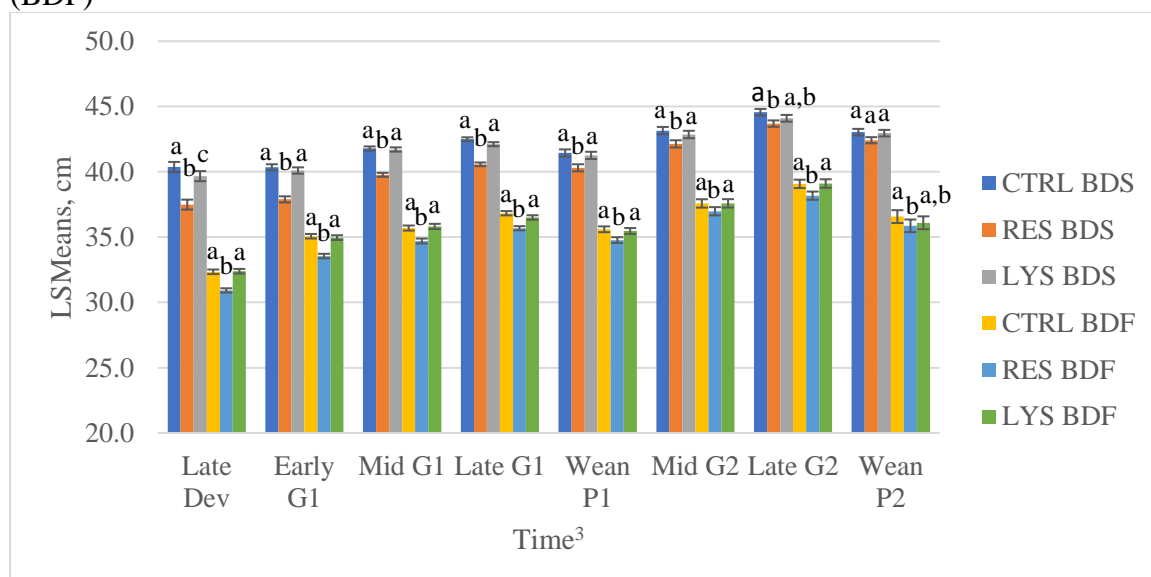
<sup>2</sup>P1 = parity 1, P2 = parity 2, LFI = feed intake during lactation, LWL = bodyweight loss during lactation, LBFL = backfat loss during lactation, NW = number of piglets weaned, PWM = pre-weaning piglet mortality

Diet and G1H were significant sources of variation for other production traits as well. There was an effect of diet on P1 NBA ( $P < 0.05$ ; Table 3.2) in which gilts fed the RES developmental diet had  $1.1 \pm 0.4$  more piglets born alive when compared to gilts fed the LYS developmental diet; sows fed the CTRL developmental diet had intermediate NBA that was not significantly different from sows fed either the RES or LYS dietary treatments. However, developmental diet did not affect P1 TNB or SB ( $P > 0.1$ ). Diet by G1H interaction was a source of variation for both TNB and NBA in P2 ( $P < 0.05$ ). Gilts housed in stalls and fed the RES developmental diet had  $1.8 \pm 0.7$  and  $1.4 \pm 0.7$  more piglets total born and born alive, respectively, when compared to gilts housed in pens and fed the RES developmental diet. Differences between G1H for P2 TNB and NBA were marginal ( $P < 0.1$ ) in gilts fed the LYS diet with gilts housed in pens having increased TNB and NBA compared to gilts housed in stalls. Gestation housing system was a source of variation for P2 NW ( $P < 0.05$ ; Table 3.3), where gilts housed in stalls weaned  $0.5 \pm 0.2$  more piglets per litter than gilts housed in pens. In P2 PWM, G1H had an effect ( $P <$

0.05; Table 3.3) because gilts housed in pens had  $4.3 \pm 1.9$  percent greater PWM than gilts housed in stalls. Finally, developmental diet had an influence on P1 AdjTWW ( $P < 0.05$ ; Table 3.2) in which gilts fed the RES developmental diet weaned litters that were  $2.5 \pm 1.0$  kg heavier than gilts fed the CTRL diet.

### 3.4.2 Effects of Diet and Gestation Housing System on Conformation Traits

Figure 3.3. Effect of developmental diet<sup>1</sup> on body depth at the shoulder (BDS) and flank (BDF)<sup>2</sup>



<sup>1</sup>Dietary treatments were a standard corn-soybean meal diet (CTRL), an energy restricted diet via 40% inclusion of soyhulls (RES), and a diet with standard energy and increased lysine (LYS).

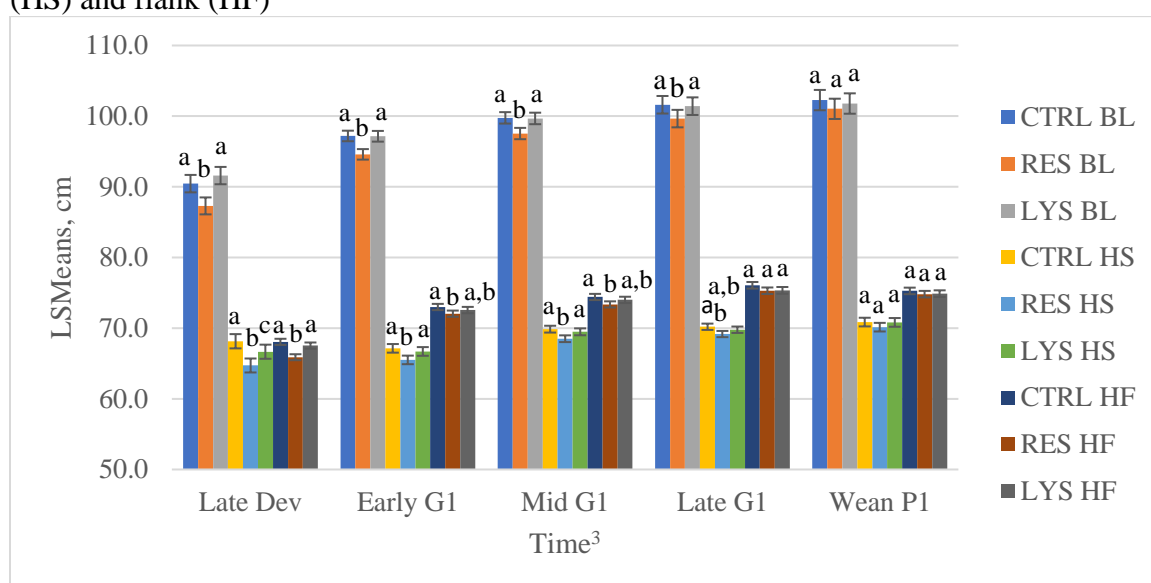
<sup>2</sup>Diets with different superscripts differ within trait and time ( $P < 0.05$ ).

<sup>3</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2

Developmental diet was a significant source of variation for objectively measured body size traits ( $P < 0.05$ ) lasting through late G1 for BL and HS, mid G1 for HF, late G2 for BDS, and wean P2 for BDF (Figures 3.3 and 3.4). In general, sows fed the RES gilt development diet were smaller than sows fed the CTRL or LYS diets by 0.5 to 2.5 cm. Developmental dietary treatment was involved in significant interaction effects with both

cohort and G1H that were not consistent across time for body depth and height traits. While generally less important, G1H affected body size traits during G1, namely early G1 BL, mid G1 BDF, mid and late G1 HS, and early, mid, and late G1 HF ( $P < 0.05$ ). Cohort by G1H interactions were also present at P1 late gestation for HS and HF ( $P < 0.05$ ). Gilts housed in pens were taller, while gilts housed in stalls were longer and deeper. Differences were small at 1.3 cm or less.

Figure 3.4. Effect of developmental diet<sup>1</sup> on body length (BL) and height at the shoulder (HS) and flank (HF)<sup>2</sup>



<sup>1</sup>Dietary treatments were a standard corn-soybean meal diet (CTRL), an energy restricted diet via 40% inclusion of soyhulls (RES), and a diet with standard energy and increased lysine (LYS).

<sup>2</sup>Diets with different superscripts differ within trait and time ( $P < 0.05$ ).

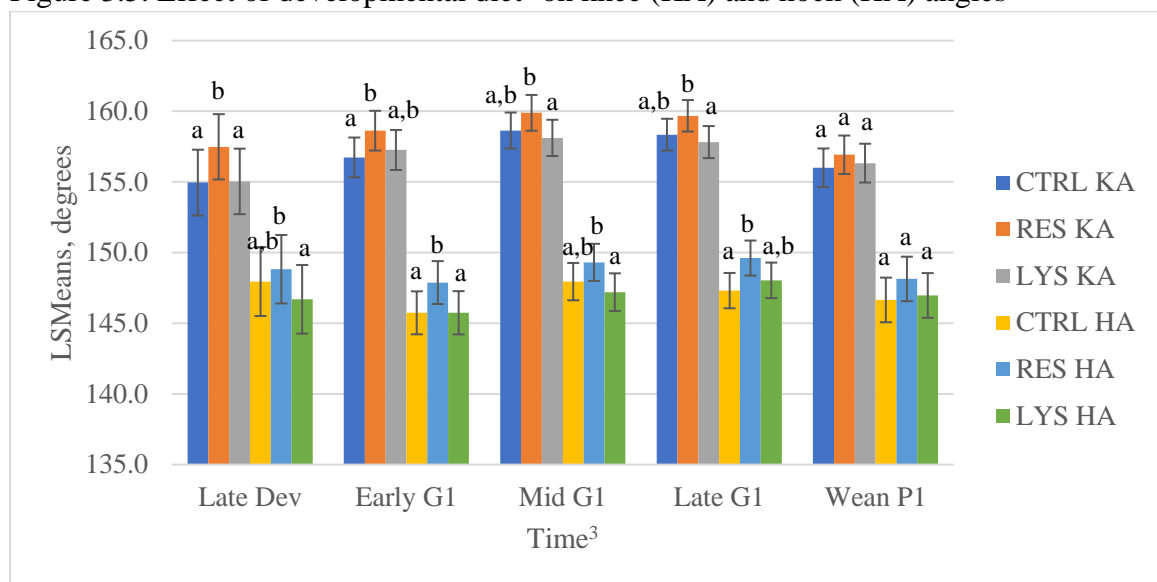
<sup>3</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1

Developmental diet was a source of variation for objectively measured KA and HA in early, mid, and late G1 ( $P < 0.05$ ; Figure 3.5). Gilts fed the RES diet during development had knee and hock angles that were two degrees greater compared to gilts fed the CTRL and LYS developmental dietary treatments. Conversely, G1H was a significant source of variation for objectively measured FP, RP, and RS at early, mid, and



late G1 for RP and RS and at mid and late G1 for FP ( $P < 0.01$ ). Gilts housed in pens had straighter pasterns by two degrees than gilts housed in stalls (Figure 3.6). Interactions between G1H and cohort were present at mid and late G1 for FP and early G1 for RP ( $P < 0.05$ ). The interaction between G1H and diet was a source of variation for RP at mid G1 ( $P < 0.01$ ). Gilts housed in pens had greater RS than gilts housed in stalls by three degrees at early G1 and two degrees at mid and late G1 (Figure 3.7).

Figure 3.5. Effect of developmental diet<sup>1</sup> on knee (KA) and hock (HA) angles<sup>2</sup>



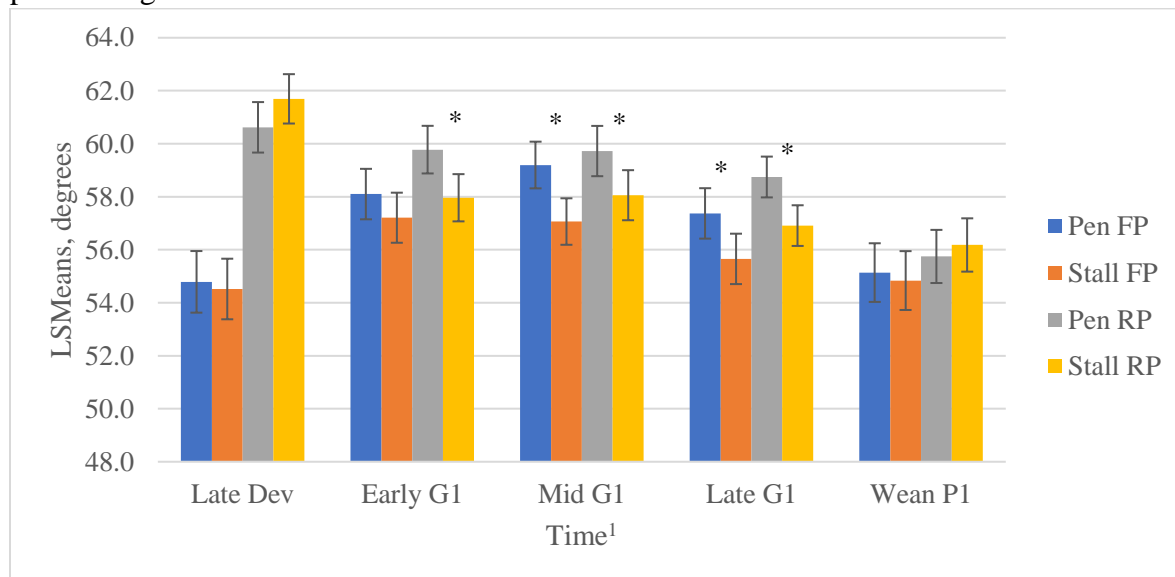
<sup>1</sup>Dietary treatments were a standard corn-soybean meal diet (CTRL), an energy restricted diet via 40% inclusion of soyhulls (RES), and a diet with standard energy and increased lysine (LYS).

<sup>2</sup>Diets with different superscripts differ within trait and time ( $P < 0.05$ ).

<sup>3</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1

Gestation housing system was a source of variation for objectively measured front foot directional position (Figure 3.8) at every time point from early G1 to late G2 ( $P < 0.05$ ). The front foot of sows housed in pens were more “toed out” than the front foot of sows housed in stalls by three to four degrees during G1, by 4.5 degrees at wean P1; the differences were reduced to 1.5 to two degrees during G2. These effects are complicated by significant higher order interactions that are not consistent across time. Diet and

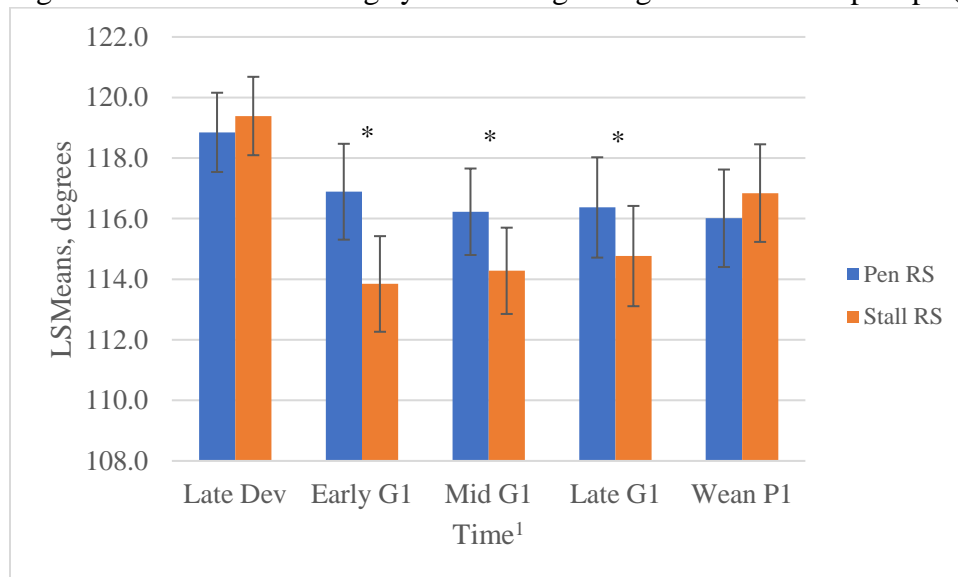
Figure 3.6. Effect of housing system during first gestation on front (FP) and rear (RP) pastern angles



\*Difference between pens and stalls within foot and time ( $P < 0.01$ ).

<sup>1</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1

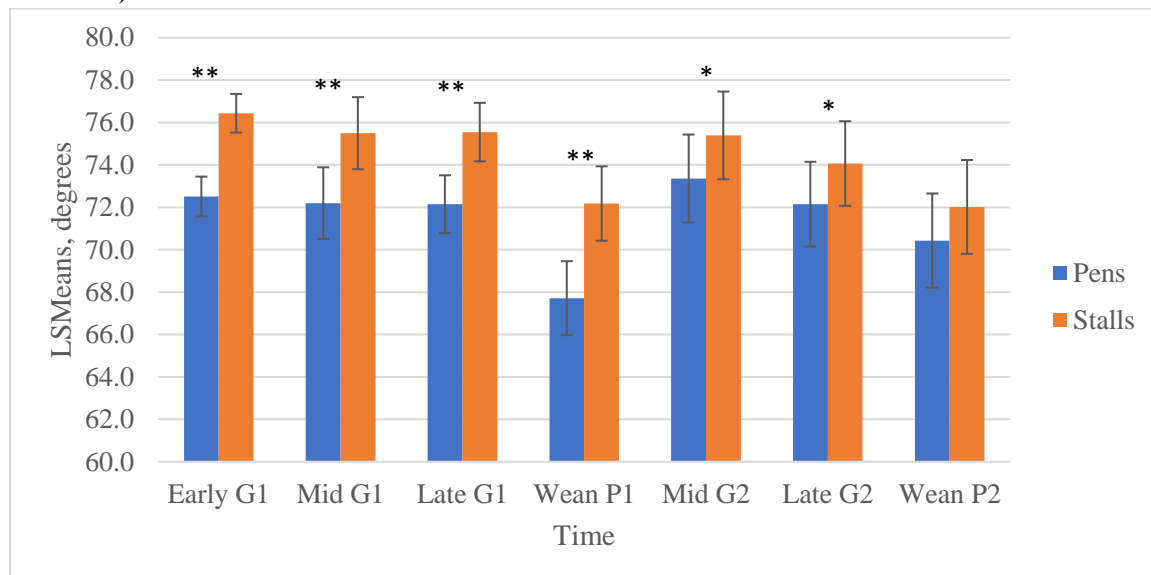
Figure 3.7. Effect of housing system during first gestation on rump slope (RS)



\*Difference between pens and stalls within time ( $P < 0.01$ )

<sup>1</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1

Figure 3.8. Effect of housing system during first gestation on foot positioning (i.e., toed in or out) on the front foot



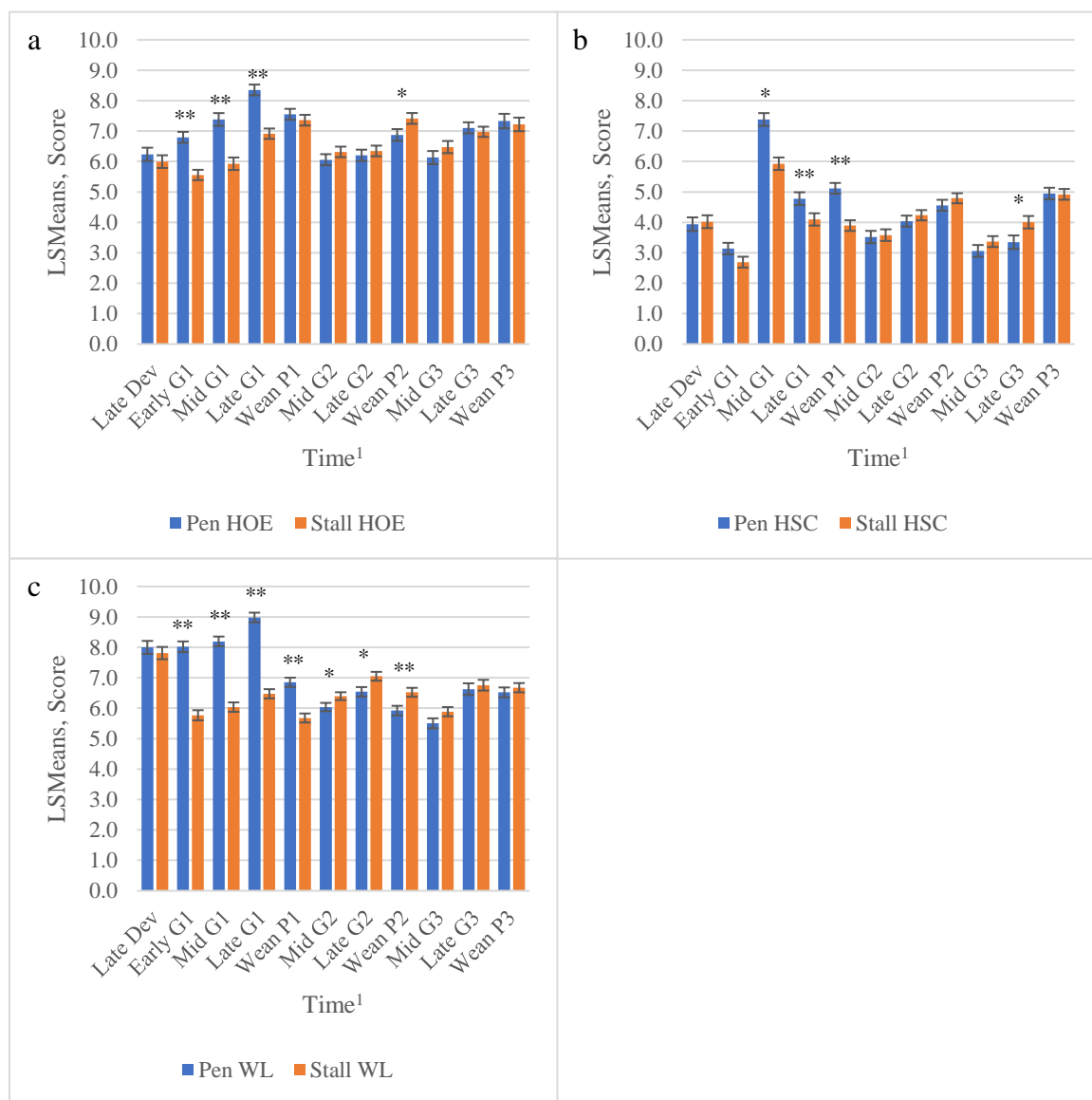
\*Difference between pens and stalls within foot and time ( $P < 0.05$ ); \*\*Difference between pens and stalls within foot and time ( $P < 0.01$ ).

<sup>1</sup>Time of trait measurement. Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2

cohort differentially influenced how sows' feet responded to gestation housing system treatments with some combinations of treatments resulting in significant effects while no differences were observed in others. Developmental diet was not a major contributor in the determination of the directional positioning of the front foot. The only effect involving diet was TIOF at wean P2 ( $P < 0.05$ ). The rear foot was not heavily influenced by diet or G1H, though G1H had an effect at mid G2 ( $P < 0.05$ ). The rear foot of sows housed in stalls were more "toed out" by 2.3 degrees when compared to sows housed in pens at mid G2.

Gestation housing system was a source of variation for foot lesions during G1 (Figures 3.9 to 3.11). Specifically, G1H affected HOE at early, mid, and late G1, HSC at mid and late G1 and wean P1, and WL from early G1 to wean P1 ( $P < 0.05$ ). Front, rear, and all lesion totals exhibited G1H effects from early G1 to wean P1 ( $P < 0.05$ ). In all

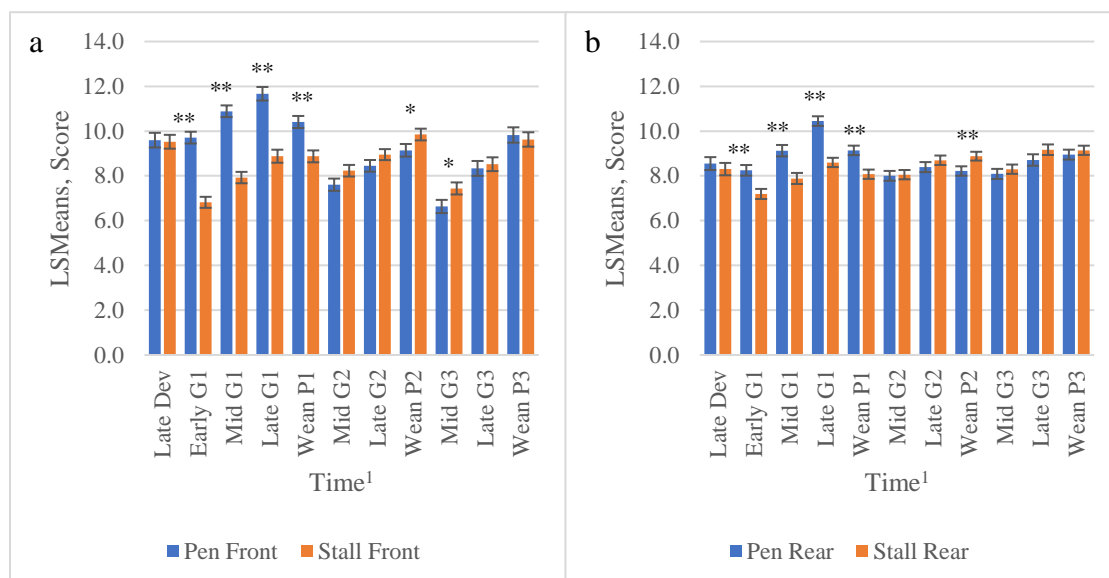
Figure 3.9. Effect of housing system during first gestation on a) heel overgrowth and erosion (HOE), b) heel-sole crack (HSC), and c) white line crack (WL) lesions



\*Difference between pens and stalls within time ( $P < 0.05$ ); \*\*Difference between pens and stalls within time ( $P < 0.01$ ).

<sup>1</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3

Figure 3.10. Effect of housing system during first gestation on total lesion score on the a) front and b) rear feet

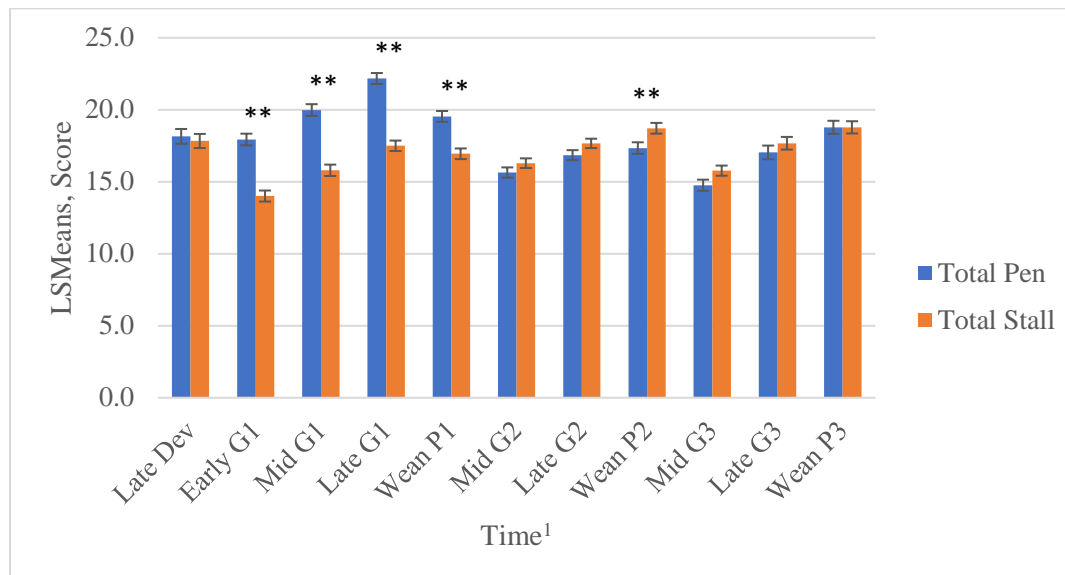


\*Difference between pens and stalls within time ( $P < 0.05$ ); \*\*Difference between pens and stalls within time ( $P < 0.01$ ).

<sup>1</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 100 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3

cases prior to G2, sows housed in pens had higher lesion scores than sows housed in stalls, indicating more severe foot lesions. Interactions between G1H and cohort were present during G1 and at wean P1 ( $P < 0.05$ ), with the exceptions of early G1 and wean P1 rear lesion total ( $P < 0.1$ ) and wean P1 front lesion total ( $P > 0.1$ ). Sows housed in pens during G1 had less HOE at wean P2 and fewer WL at mid G2 through wean P2 ( $P < 0.05$ ) compared to sows housed in stalls; those differences, however were smaller compared to differences detected in G1. Reduced lesion scores in sows housed in pens compared to sows housed in stalls were also observed at wean P2 in total front, rear, and all foot scores ( $P < 0.05$ ) and remained significant ( $P < 0.05$ ) through mid G3 for the front score.

Figure 3.11. Effect of housing system during first gestation on total lesion score on all feet



\*Difference between pens and stalls within time ( $P < 0.05$ ); \*\*Difference between pens and stalls within time ( $P < 0.01$ ).

<sup>1</sup>Time of trait measurement. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3

Developmental diet did not play a major long-term role in foot lesion scores.

However, gilt developmental diet was a source of variation for HOE at late dev, WL at early G1, rear feet total from late dev to late G1, and all feet total at early G1 ( $P < 0.05$ ).

In most cases, sows fed the RES developmental diet had the lowest foot lesion scores while sows fed the CTRL diet had the highest lesion scores; sows fed the LYS developmental diet were usually intermediate and not different from sows fed either the CTRL or RES developmental diets. However, sows fed the LYS developmental diet had the lowest lesion scores for WL at early G1, and sows fed both the RES and LYS developmental diets were different from sows fed the CTRL diet ( $P < 0.05$ ). Diet by GIH interactions were a source of variation for early G1 WL and mid G1 HSC ( $P <$

0.05); diet effects varied between pens and stalls in early G1 WL, and G1H was only a source of variation for mid G1 HSC in sows fed the LYS diet during gilt development.

### **3.5 Discussion**

#### **3.5.1 Effects of Diet and Gestation Housing System on Reproductive Longevity and Production**

Sow reproductive longevity is of high economic importance to the swine industry but is difficult to define and measure due to expression late in life. Censored records are a feature of longevity research as many sows are often unable to express their full reproductive longevity potential during the study period. Effects of developmental diet and G1H on reproductive longevity traits were modeled with both survival analysis and linear models. Survival analysis is considered theoretically superior to linear models to evaluate longevity traits as it allows for censoring of observations, modeling non-normal distributions, and modeling of time-dependent effects (Caraviello et al., 2004; Serenius and Stalder, 2006). In the present study, both methods provided the same result in which there were no significant effects of developmental diet, G1H, or their interaction on length of life and lifetime prolificacy traits. In previous work (Wijesena et al., 2017), 13 cohorts of pigs of similar genetics were assigned to dietary treatments similar to CTRL and RES during development. Energy restriction increased probability to produce parities 2 and 3. The discrepancy between trait definitions for longevity—as a binary trait in Wijesena et al. (2017) and a continuously measured trait the present study—may be a reason for differing results. Another difference between the two studies is that age at puberty was included as a covariate in the models fitted by Wijesena et al. (2017) as

energy restriction was found to increase age at puberty (Miller et al., 2011). However, early age at puberty was associated with increased reproductive longevity in sows with similar genetics to those in the present study (Tart et al., 2013). Associations between early age at puberty and increased stayability to parity 4 were also reported in other studies (Knauer et al., 2010). The energy restriction strategy was effective at slowing growth and fat deposition, with gilts fed the CTRL and LYS diets reaching mature BW at an earlier age than gilts fed the RES diet. Body weight differences between sows fed the RES developmental diet and the non-restricted diets persisted until P2 weaning, while backfat differences remained until farrowing P3. Reduced growth rate has been shown to increase age at puberty (Hutchens et al., 1981; Kummer et al., 2009). Other studies have reported that energy restricted feeding had no effect on sow longevity, including feeding *ad libitum* or 60 or 75% of *ad libitum* prior to breeding to achieve specific BW at breeding (Newton and Mahan, 1993) and feeding either 6 or 9 Mcal/ME per day to gestating sows through 4 parities (Hoppe et al., 1990).

Studies evaluating gestation housing system effects on reproductive longevity have produced mixed results, likely due to differences in group size and makeup (i.e., number of sows in pens, static vs. dynamic groups, parity of sows penned together), facility design, and feeding system (floor feeding, half-stalls, walk-in lock-in stalls, electronic sow feeders, etc.; Stalder et al., 2007). Additional factors which differ between group housing systems that could lead to differences in reproductive longevity include genetics, bedding, stocking density, feed intake, and management quality (Koketsu and Iida, 2017). Different longevity definitions and culling criteria also likely play a role in whether dietary and housing treatments result in different longevity outcomes. Anil et al.



(2005) reported that the proportion of sows culled within their single parity study period was greater for sows housed in group pens with electronic sow feeders than sows housed in stalls. Li et al. (2014) compared two sow gestation housing environments and reported that stall housing had an advantage over group pen housing for proportion of sows completing parity 3, but the housing treatments were applied for three parities before the differences became large enough to reach full significance. Across three parities, sows housed in stalls had more piglets born, born alive, and weaned than sows housed in pens (Li et al., 2014). In a review, Koketsu and Iida (2017) found stalls to be advantageous for farrowing rate in two studies, no differences were observed in one study, and an improvement of farrowing rate with pen housing was observed in another. Likewise, in review of older studies, Stalder et al. (2007) found variable results. Timing and duration of both treatments in this present study were relatively early and short term in relation to the overall reproductive longevity of these sows and likely contributed to no significant differences being observed.

Both developmental diet and gestation housing system had effects on feed intake and weight and backfat loss during lactation. The sows fed CTRL and LYS diets during development had greater BW and backfat entering P1 lactation than the RES fed females and did not consume as much feed resulting in greater BW and backfat loss during P1 lactation. These results agree with earlier reported findings where nine previous cohorts with similar genetics were utilized (Barnett, 2017). Other studies have reported mixed results. No differences in feed intake and weight loss during lactation between sows fed energy restricted and standard diets during development were observed when BW and body composition differences were no longer present by P1 farrowing (Gregory, 2021).

Feed restriction during gilt development increased both feed intake and BW loss during P1 lactation (Newton and Mahan, 1993). Sows fed 6 Mcal ME per day during gestation consumed more feed during lactation than sows fed 9 Mcal ME per day (Hoppe et al., 1990). In P2 lactation, sows fed the RES developmental diet continued to consume more feed when compared to sows fed the CTRL and LYS developmental diets, though the difference was reduced compared to P1 and did not result in significant differences in LWL and LBFL. While still significant, differences in BW between the developmental dietary treatments diminished prior to farrowing P2, leading to smaller differences in feed intake and body condition loss. Gestation housing system influenced LFI and LWL in P1 and P2. During lactation, gilts housed in pens consumed more feed and lost less BW than gilts housed in stalls. These effects may be related to body condition at farrowing, as gilts housed in stalls had greater BW prior to P1 farrowing when compared to gilts housed in pens. However, BW differences between sows housed in pens and stalls in G1 did not exist by P1 weaning and does not explain differences in LFI and LWL in P2. Li et al. (2014) reported sows housed in pens for three gestations consumed 0.3 kg more feed per day during lactation when compared to sows housed in stalls in P1; however, there were no feed intake differences between sows housed in pens and sows housed in stalls in P2. Sows housed in pens tended to lose less body weight during lactation than sows housed in stalls across all three parities (Li et al., 2014). In P3 and later, developmental diet and GIH were not significant sources of variation for LFI or LWL in the present study.

Limited influence of developmental diet and P1GH on litter size traits were identified. In P1, sows fed the RES gilt developmental diet had greater NBA than sows fed the LYS diet. The RES and LYS diets differed in both energy and lysine levels, and it

is unclear whether one of these differences singly or both in combination explained the variation in NBA observed. Differences in litter size between energy levels were not reported in other studies (Hoppe et al., 1990; Newton and Mahan, 1993; Stalder et al., 2000; Klindt et al., 2001). Stalder et al. (2000) did not observe differences in litter size between dietary protein levels.

Housing system during G1 was associated with PWM and NW, but developmental diet had no effects on these traits. In P2 of the present study, sows housed in pens had greater PWM and less NW when compared to sows housed in stalls. Conversely, Anil et al. (2005) reported increased PWM in litters from sows housed in stalls compared to sows housed in pens during gestation. However, Li et al. (2014) reported sows housed in stalls had greater NW than sows housed in pens across three parities.

A dietary treatment effect on P1 AdjTWW was the only treatment effect on litter weights. No treatment effects were observed on TBW, but P1 litters from sows fed the RES developmental diet were heavier at weaning than litters from sows fed the CTRL diet when adjusted for age at weaning. When evaluating individual piglet weights from nine previous cohorts of similar genetics, Barnett (2017) reported sows fed the RES developmental diet tended to have heavier piglets at birth and weaned heavier piglets in P1 than sows fed the CTRL diet. In agreement with present findings, no differences between dietary treatments were observed in P2 birth or weaning weights (Barnett, 2017). Stalder et al. (2000) did not observe any effects of developmental diets differing in energy and protein content on P1 litter birth or weaning weights, and Gregory (2021) did not report differences in birth or weaning weights resulting from energy restricted development diets. Despite differences in timing of treatment application, reduced energy

consumption during first gestation increased litter weaning weight in P1 but had no effects on litter birth weight in P1 or P2 or litter weaning weight in P2 (Hoppe et al., 1990). This is similar to the present findings. Differences in weight, LFI, and LWL between energy restriction strategies in each study could explain differences in effects on weaning weight and other production traits observed. Gestation housing system did not influence TBW and AdjTWW, which agrees with previous findings (Anil et al., 2005; Li et al., 2014).

### **3.5.2 Effects of Diet and Gestation Housing System on Conformation Traits**

Gilt developmental diet had a significant influence on all objectively measured body size traits, but these differences diminished over time. This was not surprising, as dietary energy intake influenced body weight in the present study. It is also to be expected that the effects would lessen as additional time passed between the application of gilt development dietary treatments and the time of conformation trait measurement. In other studies, associations were observed between higher dietary energy levels during gilt development and increased body size measured during the developmental period (Calabotta et al., 1982b) and from development through P3 weaning (Barczewski et al., 1990). Gestation housing system played a smaller role in objectively measured body size traits. Reduced BL at early G1 and BDF at mid G1 of gilts housed in pens is likely associated with the decreased weight and backfat in pen-housed gilts prior to P1 farrowing. However, gilts housed in pens were taller at both the shoulder and flank at mid and late G1 and at the flank at early G1 than gilts housed in stalls. This is likely due to gilts housed in pens having straighter pasterns compared to gilts housed in stalls.

Differences in FP and RP between gilts housed in pens and stalls were significant at the same time points as differences in HS and HF, respectively.

Diet played a larger and more consistent role in KA and HA than G1H.

Differences were consistently driven by energy intake, and sows fed the RES developmental diet were straighter at the knee and hock joints throughout G1 than sows fed the CTRL and LYS developmental diets. Differences in leg conformation between dietary energy levels fed during gilt development have been previously reported. Softer front pasterns were found in sows fed higher dietary energy levels during gilt development, while no dietary energy effects were observed for hock angle or rear pastern angle objectively measured during the developmental period (Calabotta et al., 1982b). Additionally, *ad libitum* feeding and greater energy intake was associated with softer front pastern angle and tended to be associated with smaller hock angle objectively measured during development and through P3 weaning; dietary energy level, though, did not affect rear pastern angle (Barczewski et al., 1990). However, rearing intensity (feed allowance) did not influence subjective scores taken from development to fourth gestation for buck-knees, weak front pasterns, steep hock joints, and rear foot toed out; it did tend to influence weak rear pasterns where feeding diets providing greater energy restriction was advantageous (Jørgensen and Sørensen, 1998). In the present study, developmental diet was not an important source of variation for objectively measured pastern angles or foot directional position (i.e., toed in or out) traits on any foot.

Gestation housing system had consistent effects on objectively measured pastern angles and RS throughout G1, except FP at early G1. In all cases, gilts housed in pens had straighter pastern angles and greater RS. Foot directional positioning (i.e., toed in or

out) on the front foot was impacted by G1H; sows housed in pens were more “toed out” than sows housed in stalls. Conversely, the rear foot was not influenced by G1H, except at mid G2 with effects in the opposite direction as the front foot. Few other studies have assessed gestation housing system effects on conformational traits. Group pens were beneficial to leg conformation traits assessed via subjective scores in young boars as they were less “toed out” on their front feet, had straighter rear pasterns, and more favorable hock angles compared to boars housed in stalls (Hacker et al., 1994). In the present study, gilts housed in pens had straighter pasterns. However, the pasterns of gilts in the present population were straight enough for this to be a detrimental effect rather than desirable as it is described by Hacker et al. (1994). Population means, therefore, should be noted when determining what objective angle measurements are best for replacement animals across systems. Unlike Hacker et al. (1994), pen housing resulted in gilts being more “toed out”. It is unclear how “favorable” hock angle (Hacker et al., 1994) would compare to objective hock angle measurements in the present study, highlighting the need for standardized phenotyping to facilitate comparison between studies. While specific conformational traits were not assessed in sows, group housing has resulted in sows with greater lameness scores when compared to sows housed in stalls (Calderón Díaz et al., 2014; Knox et al., 2014). Lameness was not scored in the present study; however, the conformational differences observed were likely unfavorable for sows housed in pens, and greater lameness in group housed sows may be expected as a result.

Gestation housing system had effects on all foot lesion types during G1. Heel-sole cracks and WL remained significant at wean P1. When sows were housed in pens, more severe foot lesions occurred for all traits. Likewise, greater incidence and severity of foot

lesions, including HOE, HSC, and WL, were observed when sows were housed in pens compared to stalls (Anil et al., 2007). However, Calderón Díaz et al. (2014) reported that sows housed in stalls had greater risk of WL when compared with pen housed sows. Dairy cow claws soften at the white line, sole, and wall when exposed to water (Borderas, 2004) which, if consistent across species, would have inferences in swine gestation housing effects on foot lesions. Future studies should assess the effects of pen wetness and fecal soiling on foot lesions as these factors may contribute to increased foot lesion severity and conflicting results between studies. In the present study, higher WL lesion scores were observed at mid and late G2 and at wean P2 in sows housed in stalls when compared to sows housed in pens. Such was also the case for HOE, front, rear, and all lesion scores at wean P2. These effects are much smaller than those observed in P1, and their cause is unclear.

While less influential, there were significant effects of dietary treatments during gilt development on foot lesion scores, specifically, HOE at late dev, WL at early G1, total rear foot lesions from late dev to late G1, and total lesions on all feet at early G1. These differences were mostly driven by energy level as sows fed the RES developmental diet had lower foot lesion scores than sows fed the CTRL developmental diet in almost all significant cases. These results agree with Calabotta et al. (1982a) who reported that feeding higher dietary energy levels during gilt development resulted in higher incidence of heel lesions evaluated during that period. However, when followed through P3, sows previously fed energy-restricted diets during development had greater heel lesion severity on the rear outer toes (Arthur et al., 1983). No differences in foot

lesion scores associated with development diet were significant for timepoints after G1 in the present study.

While significant, most differences in objectively measured sow conformation traits observed between dietary treatments and gestation housing systems were numerically small relative to trait standard deviations, and their biological meaning is unclear. More research is needed to determine how these small conformational changes observed at the population level impact individual animal welfare. The small conformational changes observed in the present study likely would not have a major impact on most individuals but may be enough to move some individuals across thresholds such as from fair to poor conformation. More research is needed with objective measurements to clearly define these thresholds at which conformation becomes poor and detrimental to sow welfare and productivity. No reproductive longevity differences were identified in this study; however, some productivity differences were observed. It is possible that many conformational trait thresholds producers use to identify sows for culling may not be as detrimental to the sow as previously thought as these sows will continue to produce litters when given the chance to remain in the herd. Both dietary and G1H treatments were only applied for a short period of time with most significant differences noted at timepoints closer to treatments. No effects of developmental diet or G1H on any objectively measured conformation trait were observed after wean P2, with effects on most traits becoming insignificant by P1 wean. Further research is needed to determine if developmental diet and gestation housing treatments would result in greater conformational differences and animal welfare consequences if applied to sows for a longer duration. In particular, additional study is



required to examine if undesirable conformational differences which started to form in G1 would continue to worsen if sows were housed in pens each gestation and result in reduced reproductive longevity of pen-housed sows. While differences were quick to disappear once conditions were standardized between groups, they were also quick to form after treatments were applied. The resilience of sows to temporary management changes may explain the lack of reproductive longevity differences between treatments. However, producers should take great care to optimize dietary and management factors when removal rates are relatively high, such as entry of gilts into the breeding herd. Furthermore, the objective measurement system employed in the present study was able to detect small differences that would have likely been missed or reported as non-significant by most subjective conformation scoring systems, providing more evidence of the value of an objective measurement system to assess conformation traits.

### **3.6 Conclusions**

Energy and lysine content of developmental diets and pen or stall gestation housing systems during first gestation affected some production traits, but not sow reproductive longevity as presently defined. Most notably, feeding restricted energy during gilt development led to increased lactation feed consumption and litter weaning weight and reduced BW and backfat loss in parity 1. Both developmental diet and gestation housing system had effects on conformation traits; developmental dietary treatment influenced body size traits and knee and hock angles while gestation housing system affected rump slope, pastern angles, front foot directional position (i.e., toed in or out), and foot lesions. Differences in conformation due to developmental diet and G1H treatments developed rapidly after treatments were applied but diminished quickly after

treatments were no longer imposed. While differences in conformation traits between treatments were numerically small, many persisted across multiple time points and demonstrated the ability of the objective conformation trait measurement system to identify differences that would likely be missed if assessed using subjective scores and facilitate direct comparison across studies.

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## **CHAPTER 4: OBJECTIVELY MEASURED CONFORMATION TRAITS OVER TIME AND ASSOCIATIONS WITH REPRODUCTIVE LONGEVITY IN SOWS**

### **4.1 Abstract**

Selection of replacement gilts occurs early in life and is based largely on conformation. However, little is known about how conformation changes over time or its specific effects on sow reproductive longevity. Therefore, changes in conformation traits over time were quantified, and effects of conformation traits on sow reproductive longevity were assessed. Conformation traits considered included five body size traits, knee, hock, and pastern angles, rump slope, and angles measuring directional position of the foot (toed in/out). They were objectively measured from video recordings of sows ( $n = 622$ ) collected at 16 time points between 112 d of age and parity (P) 4 weaning. Three types of foot lesions were scored at the same time points. All traits exhibited significant changes over time ( $P < 0.01$ ). Body size increased as animals aged, with most growth observed prior to first breeding, though slower growth continued during gestation (G) through P4. Knee and front and rear pastern angles decreased by 10.3, 5.7, and 7.8 degrees, respectively, between 112 days of age and P4 weaning, with most change occurring during development and lactation. Hock angle, rump slope, and foot direction (toed in/out) traits did not exhibit a strong directional trend over time. However, rump slope tended to be the greatest in middle and late development and at weaning, while the front foot was most “toed out” and the rear foot was most straightforward at weaning. Heel overgrowth and erosion and heel-sole cracks tended to be most severe at weaning while white line cracks improved over time. Based on fitting Cox proportional hazards models, associations were identified ( $P < 0.05$ ) between life on

test, defined as the number of days between the start of development and culling, and several conformation traits. These traits were height at the flank at 112 d of age, height at the shoulder and flank and body depth at the flank at 206 d of age, rear foot direction (toed in/out) and total rear foot lesions at mid G1, and body depth at the shoulder and heel-sole cracks at P1 weaning. Taller height, smaller body depth, more “toed out” rear feet, and increased foot lesion severity increased the risk (hazard) of culling. Quadratic terms for knee angle at 112 and 206 days of age and front pastern angle at P1 weaning were also associated with life on test ( $P < 0.05$ ). Both straight and soft knees increased removal hazard, but intermediary front pastern angles surprisingly resulted in decreased life on test. These results provide more specific evidence of conformation changes over time and associations with reproductive longevity to consider when selecting replacement gilts.

## **4.2 Introduction**

Selection based on conformation is typically performed via visual appraisal early in a gilt’s life prior to breeding. At the time of selection, however, gilts are still in the rapid growth phase (Robison, 1976), and it is plausible that conformation changes could accompany growth. Very few studies have compared conformation traits at different times in an animal’s life (de Sevilla et al., 2009; Stock et al., 2018), and these studies only compared two or three time points prior to parity (P) 3, the point at which the sow covers her development and maintenance costs to become profitable (Stalder et al., 2003; Mote et al., 2008). Therefore, it remains unknown if and how conformation traits change over time and whether selection for conformational characteristics considered as “good”



by stockpersons early in life is effective at selecting for structural integrity later in life and, consequently, sow reproductive longevity.

Recommendations for conformation trait-based selection are well established within the swine industry; however, scientific evidence to support them is limited. Most studies that associate conformation and reproductive longevity are based on subjective scores that encompass multiple aspects of conformation in one score. Only two studies were identified that evaluated specific conformation traits and longevity. de Sevilla et al. (2008) assessed the effects of specific morphological defects on longevity, and Nikkilä et al. (2013) estimated genetic correlations between 17 specific conformation traits and longevity. Furthermore, objective measurement systems provide greater accuracy and precision than traditional subjective scoring systems (Stock et al., 2017) and can successfully identify subtle conformation changes (chapter 3). Therefore, the objectives of this study were to perform an in-depth assessment of changes in sow conformation traits over time between 112 days of age and P4 weaning and to evaluate the effects of conformation traits on sow reproductive longevity using objective conformation trait measurements.

## **4.3 Materials and Methods**

### **4.3.1 Animals and Management**

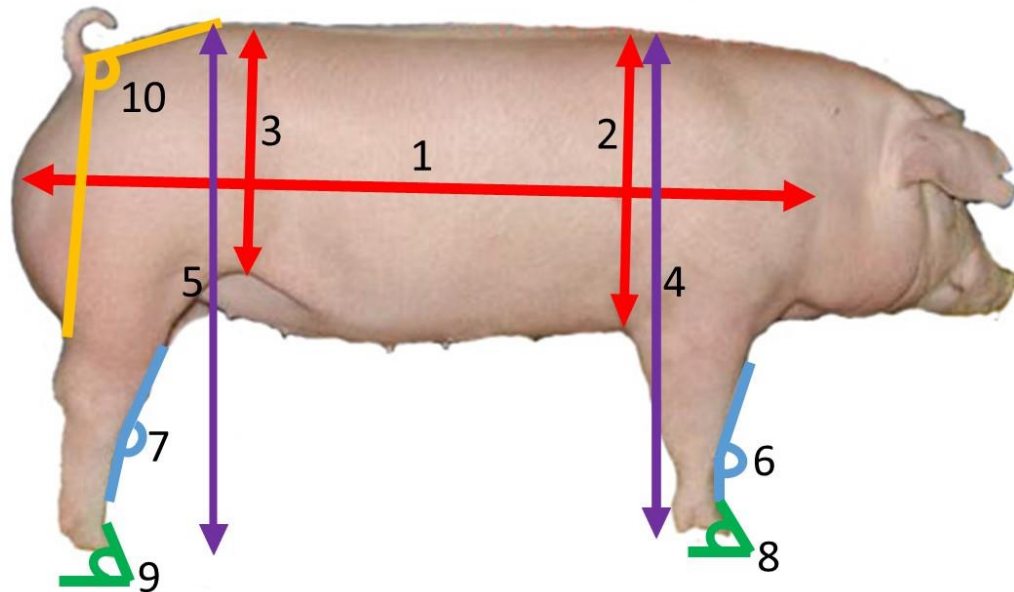
All procedures involving animals were approved by the University of Nebraska Institutional Animal Care and Use Committee protocol number 1859. Animal management was described in chapter 3. Briefly, gilts ( $n = 622$ ) were developed in 5 cohorts. During the developmental period from 112 days of age to 225 (cohorts 1 and 2)

or 209 (cohorts 3 to 5) days of age, gilts were allocated to 1 of 3 developmental diets: a standard corn-soybean meal diet (CTRL), an energy restricted diet via inclusion of 40% soyhulls (RES) with similar amino acids and other nutrients as CTRL, and a diet with the same metabolizable energy (ME) as CTRL and same Lysine to ME ratio as RES (LYS). All gilts were fed the same gestation and lactation diets. During first gestation (G), half of the gilts were allocated to pen housing while half were allocated to stall housing in cohorts 1 and 3 to 5. All sows were housed in stalls in cohort 2. In G 2 to 4, all sows were housed in stalls. Sows remained in production through four parities and were culled only for reproductive failure or animal welfare reasons. Removal dates and reasons were recorded, and life on test was calculated as the number of days between the developmental period start date and culling date.

#### **4.3.2 Conformation Trait Data Collection**

Conformation data was collected as described in chapter 2 at 112.3 ( $\pm 4.3$ ), 167.1 ( $\pm 3.4$ ), and 206.3 ( $\pm 6.4$ ) days of age, at day 30.2 ( $\pm 6.5$ ) of G1, at 58.4 ( $\pm 6.7$ ) and 98.9 ( $\pm 5.2$ ) of G 1 to 4, and 1.6 ( $\pm 1.9$ ) days after weaning in P1 to 4 (hereafter “early dev”, “mid dev”, “late dev”, “early G”, “mid G”, “late G”, and “wean P”). Twelve objectively measured traits were utilized in this analysis. Side view traits (Figure 4.1) were body length (BL), body depth at the shoulder (BDS) and flank (BDF), height at the shoulder (HS) and flank (HF), knee angle (KA), hock angle (HA), front and rear pastern angle (FP and RP, respectively), and rump slope (RS). Angles assessing the directional position of the foot (i.e., toed in or out; Figure 4.2) were measured on the front (TIOF) and rear (TIOR) left feet. The foot was facing straight forward if the angle was 90 degrees while angles less than 90 degrees indicated “toed out” feet and angles greater than 90 degrees

Figure 4.1. Side view conformation traits measured.



1 = body length (BL, cm), 2 = body depth at the shoulder (BDS, cm), 3 = body depth at the flank (BDF, cm), 4 = height at the shoulder (HS, cm), 5 = height at the flank (HF, cm), 6 = knee angle (KA, degrees), 7 = hock angle (HA, degrees), 8 = front pastern angle (FP, degrees), 9 = rear pastern angle (RP, degrees), 10 = rump slope (RS, degrees)

indicated “toed in” feet. Side view traits were measured at all time points, while foot directional position traits were measured beginning at early G1 by two or three evaluators. Three types of foot lesions were scored on a scale of 0 to 3 using the FeetFirst® Lesion Scoring Guide (Zinpro Corporation, Eden Prairie, MN) at the same timepoints starting at late dev in cohorts 3 to 5. The scores from each foot were summed to create a total score from 0 to 12 for each lesion type. Scores of all lesion types on the front feet, rear feet, and all feet were also summed.

#### 4.3.3 Statistical Analysis

To assess conformational changes over time, the data were analyzed with repeated measures linear mixed models using the lme function from the nlme package (Pinheiro et

Figure 4.2. Foot directional positioning (i.e., toed in or out) angle measurement<sup>1</sup>

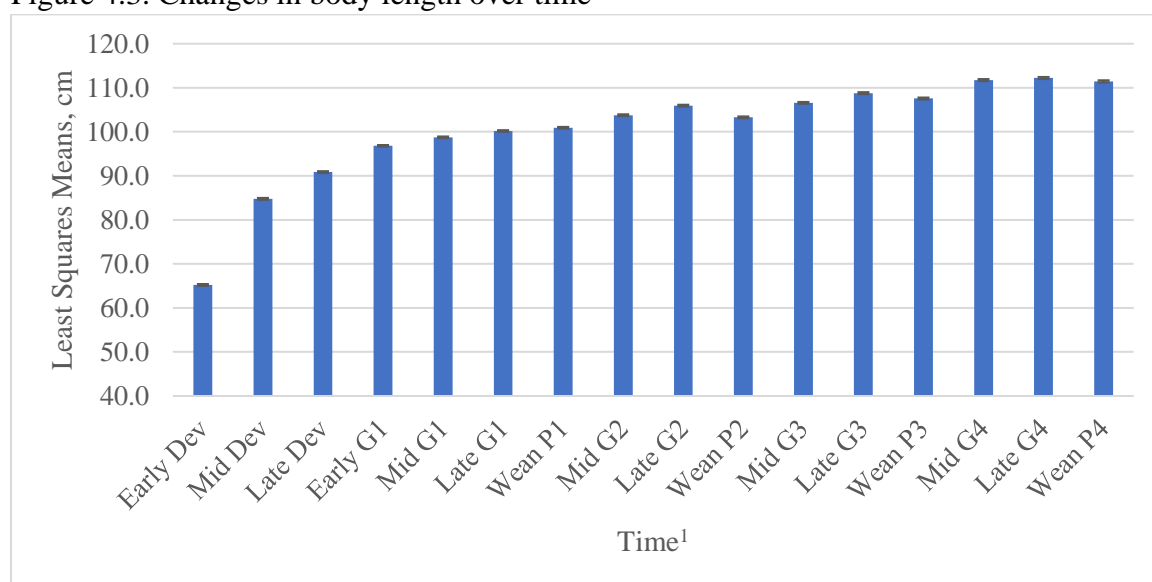


<sup>1</sup>Angles assessing directional position of foot (i.e., toed in or out) on the front (TIOF) and rear (TIOR) left feet, measured in degrees.

al., 2020) in R v.4.0.3 (R Core Team, 2020). Cohort, developmental diet, G1 housing system, time, and all interactions that could be modeled without confounding were initially modeled. After removal of insignificant effects ( $P > 0.1$ ), final models for foot directional position (i.e., toed in or out) traits included fixed effects of cohort, diet, G1 housing system, time, diet x G1 housing system, diet x time, and G1 housing system x time. For all side view traits, fixed effects in the final model were cohort, diet, G1 housing system, time, diet x G1 housing system, diet x time, G1 housing system x time, and diet x G1 housing system x time. Final models for foot lesion traits included fixed effects of cohort, diet, G1 housing system, time, all 2-way interactions, cohort x G1 housing system x time, and diet x G1 housing system x time. Animal, evaluator, and residual were random effects for all conformation traits measured by multiple evaluators, while models for foot lesion traits only included animal and residual as random effects. Different covariance structures were tested with a representative subset of traits, and AIC

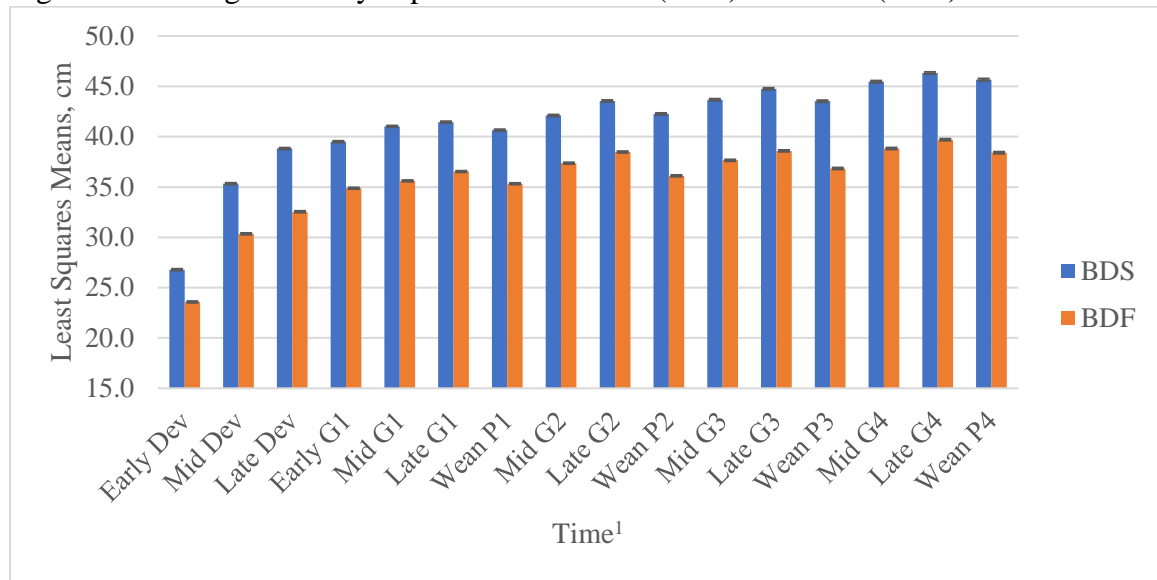
and BIC values were compared. The exponential spatial correlation structure including a nugget effect was used in final models as it consistently ranked in the top three covariance structures for lowest AIC and BIC across traits; time was the covariate grouped by evaluator nested within animal or just animal in the case of foot lesion traits. The animal effect was removed from the model for the total lesion score on all feet because no animal variance was detected. Type III ANOVAs were run using the Anova function from the car package (Fox and Weisberg, 2019). Least squares means and pairwise comparisons with the Tukey adjustment (Tukey, 1949) were calculated with the emmeans package and function (Lenth, 2020).

Figure 4.3. Changes in body length over time



<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Figure 4.4. Changes in body depth at the shoulder (BDS) and flank (BDF) over time



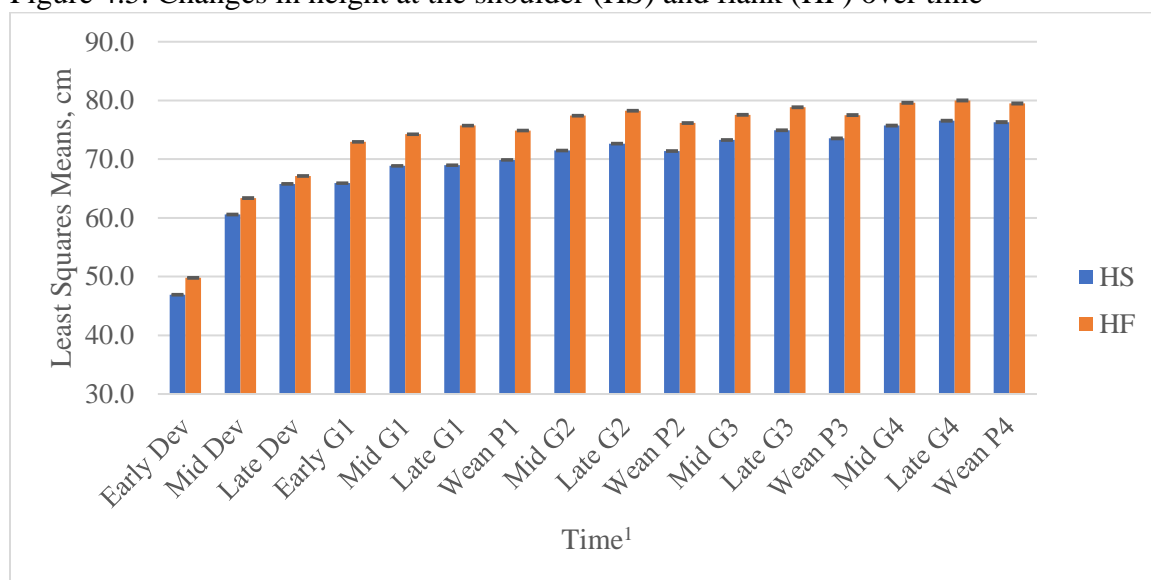
<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of the development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Cox proportional hazards models (Cox, 1972) were constructed using coxme (Therneau, 2020) in R v.4.0.3 (R Core Team, 2020) to investigate the relationship between conformation traits and reproductive longevity. Life on test was the reproductive longevity metric analyzed. Sows that remained in the herd through wean P4 were considered to have censored records. Multiple measurements of the same sow and trait at the same time point were averaged. Cohort and diet were fixed effects and sire was a random effect in every model. Housing system during G1 was a fixed effect in models including conformation traits that were measured after breeding. Separate models were fit for each conformation trait and foot lesion at early dev, late dev, mid G1, and wean P1. Effects of foot directional position (i.e., toed in or out) traits on reproductive longevity were analyzed at early G1 rather than during development because these traits were not

measured during development. Because leg angles measured from the side view are expected to have intermediate optimum values, quadratic Cox proportional hazards models were fit for KA, HA, FP, and RP at early dev, late dev, mid G1, and wean P1.

#### 4.4 Results

Figure 4.5. Changes in height at the shoulder (HS) and flank (HF) over time

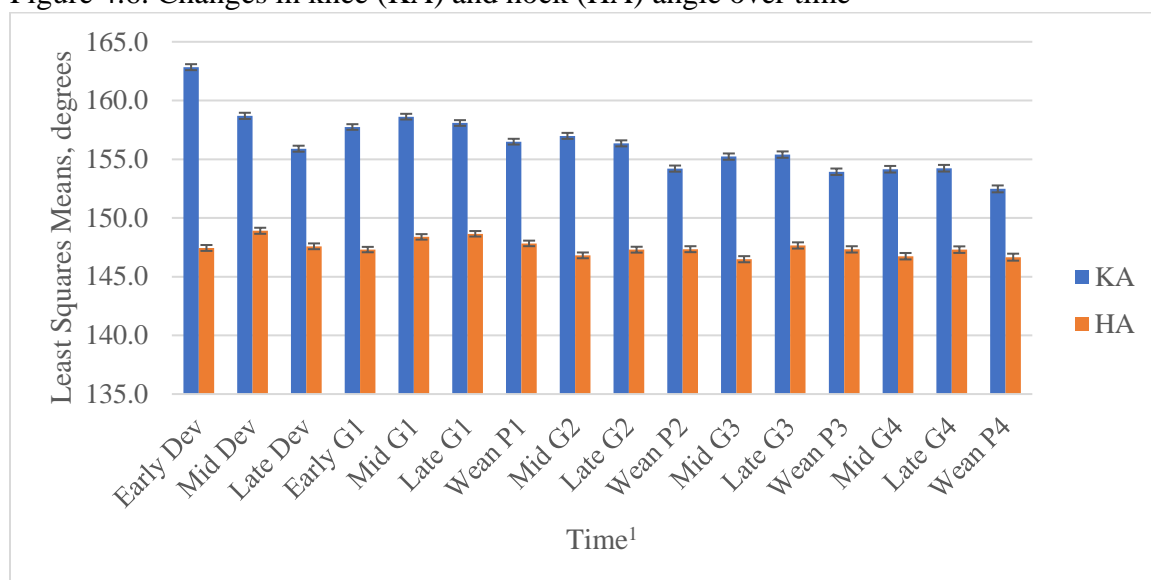


<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of the development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

All traits exhibited highly significant changes over time ( $P < 0.01$ ). Body size traits (Figures 4.3 to 4.5) exhibited the most growth during development, but slower growth continued through wean P4. Growth occurred during gestation, while body size decreased at weaning each parity, except BL and HS in P1. Pairwise comparisons revealed significant growth between weaning and the subsequent mid gestation in all traits and parities ( $P < 0.01$ ). Additionally, comparisons between weaning and the

previous late gestation time point indicated that the decreases observed at weaning were significant for BDS and BDF each parity ( $P < 0.01$ ), HF in P1 to 3 ( $P < 0.01$ ), and HS and BL in P2 and 3 ( $P < 0.01$ ).

Figure 4.6. Changes in knee (KA) and hock (HA) angle over time

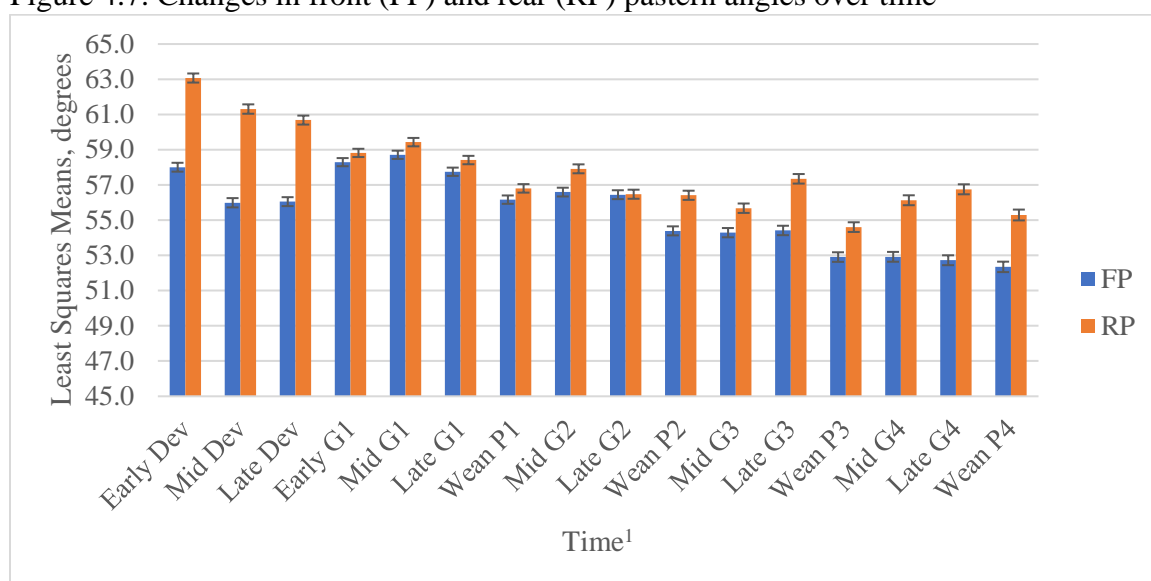


<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of the development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Knee angle (Figure 4.6) decreased by 10.3 degrees between early dev and wean P4. The largest change occurred between early and mid dev and had a magnitude of 4.1 degrees. After the developmental period, the largest decreases occurred between late gestation and weaning each parity and had magnitudes of 1.5 to 2.2 degrees. All sequential time points were significantly different in pairwise comparisons between late gestation and weaning ( $P < 0.01$ ). The knee tended to straighten back up to a smaller extent between weaning and mid gestation, though this was only significant between wean P2 and mid G3 ( $P < 0.01$ ). While significant, HA (Figure 4.6) did not exhibit



Figure 4.7. Changes in front (FP) and rear (RP) pastern angles over time

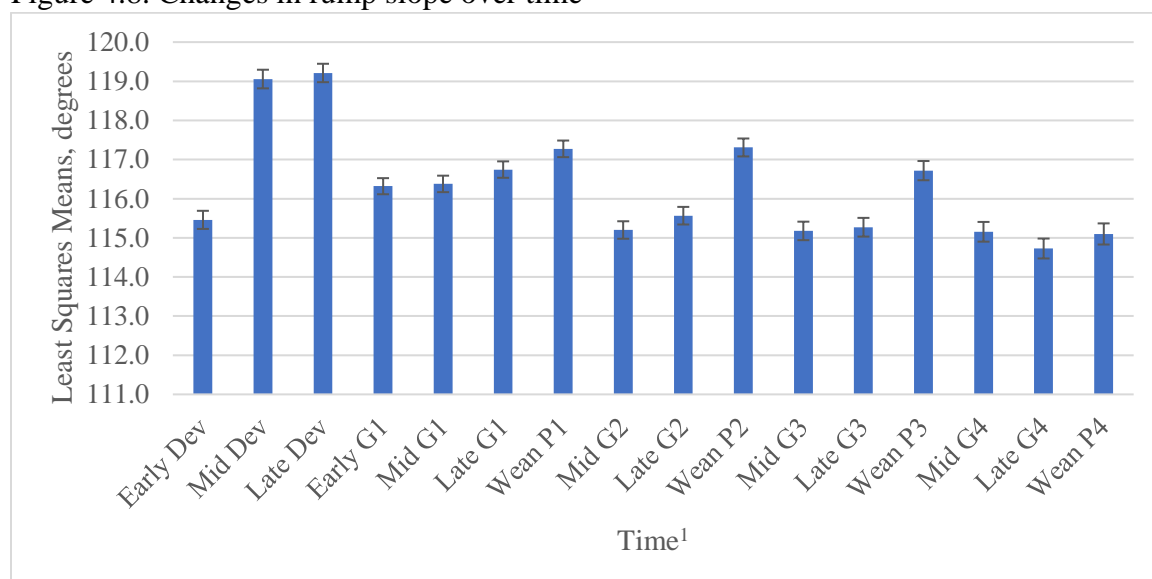


<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of the development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

appreciably large changes over time as the spread between the largest (mid dev) and smallest (mid G3) mean HA measurements was less than 2.5 degrees. A prominent pattern over time was not present for HA. However, most of the lowest measurements did occur at mid gestation in G 2 to 4. Pastern angles (Figure 4.7) exhibited small incremental changes over time that added up to a decrease of 5.7 and 7.8 degrees in FP and RP, respectively, between early dev and wean P4. A clear pattern of change over time was not readily apparent for pastern angles. However, the largest decreases tended to occur during development and between late gestation and weaning each parity, except RP in P2. Rump slope (Figure 4.8) fluctuated significantly, but overall did not increase or decrease over time. Rump slope was steepest in mid and late dev and tended to be steeper at weaning than during gestation in G1 to G3. There was a significant decrease in rump

slope between weaning and the subsequent mid gestation each parity ( $P < 0.01$ ). Changes in foot directional position (i.e., toed in or out) varied between feet (Figure 4.9). The front foot tended to be more toed out at weaning, especially in earlier parities. Conversely, the rear foot tended to be the most straightforward at weaning each parity and in early and mid G1. There was a 6.3 and 4.2 degree spread between the least and greatest mean TIOF and TIOR measurements, respectively. The least TIOF measurement occurred at wean P1, and the least TIOR measurement occurred at late G4. The greatest measurement for both TIOF and TIOR occurred at early G1.

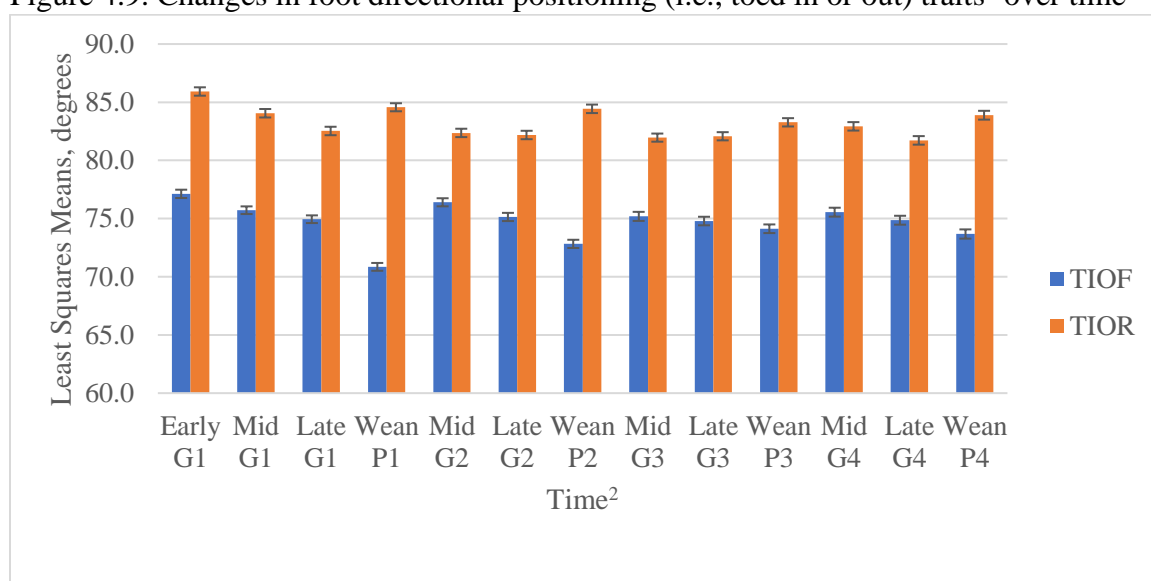
Figure 4.8. Changes in rump slope over time



<sup>1</sup>Time of trait measurement. Early Dev = near the beginning of the development period at 112 days of age, Mid Dev = near the middle of the development period at 167 days of age, Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Individual foot lesions exhibited variation in how they changed over time (Figure 4.10). Heel overgrowth and erosion (HOE) and heel sole-crack (HSC) were most severe

Figure 4.9. Changes in foot directional positioning (i.e., toed in or out) traits<sup>1</sup> over time



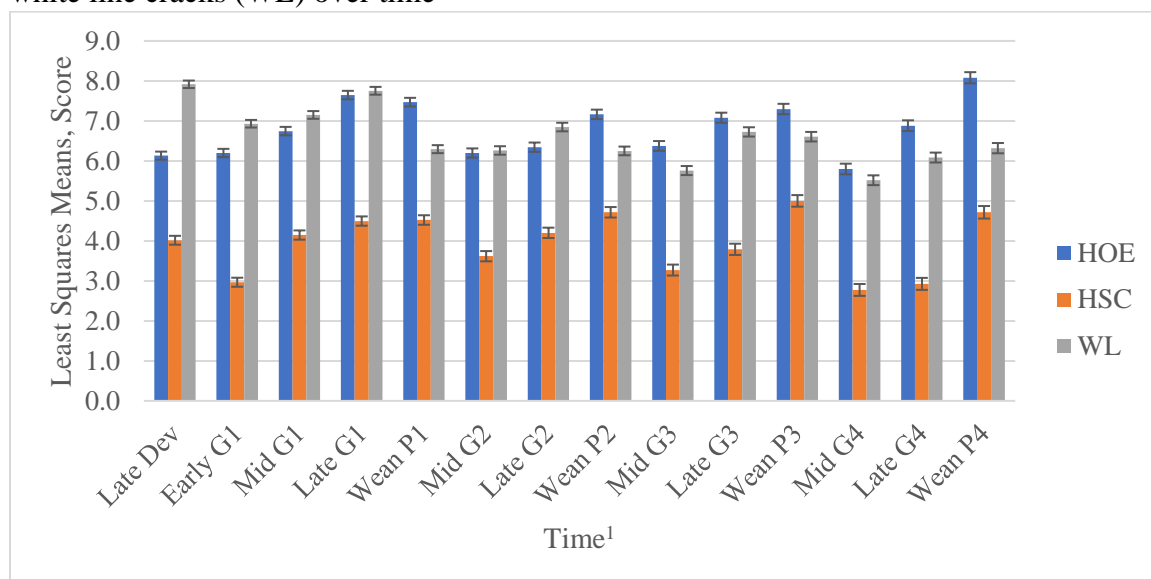
<sup>1</sup>TIOF = front foot toed in or out, TIOR = rear foot toed in or out

<sup>2</sup>Time of trait measurement. Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

at weaning and least severe at mid gestation; pairwise comparisons between sequential mid gestation and weaning time points were significant ( $P < 0.01$ ) in all cases for HOE and starting at wean P1 for HSC. A pattern over time was not detected for white line (WL); however, the highest WL scores occurred at late dev and during G1. Total front, rear, and all foot lesion scores tended to be highest during G1 and at weaning and lowest at mid gestation in G 2 to 4 (Figures 4.11 and 4.12). Pairwise comparisons of sequential mid gestation and weaning time points were significant ( $P < 0.01$ ) starting at wean P1 for total front foot score and all feet total score. This trend was not as strong in the total rear foot score and was only significant ( $P < 0.01$ ) in sequential pairwise comparisons from mid G3 to wean P4. Effects of developmental dietary treatment and first gestation

housing system on conformation traits have been addressed in chapter 3, and the effects of these variables in the present analysis closely match our previous results.

Figure 4.10. Changes in heel overgrowth and erosion (HOE), heel-sole cracks (HSC), and white line cracks (WL) over time

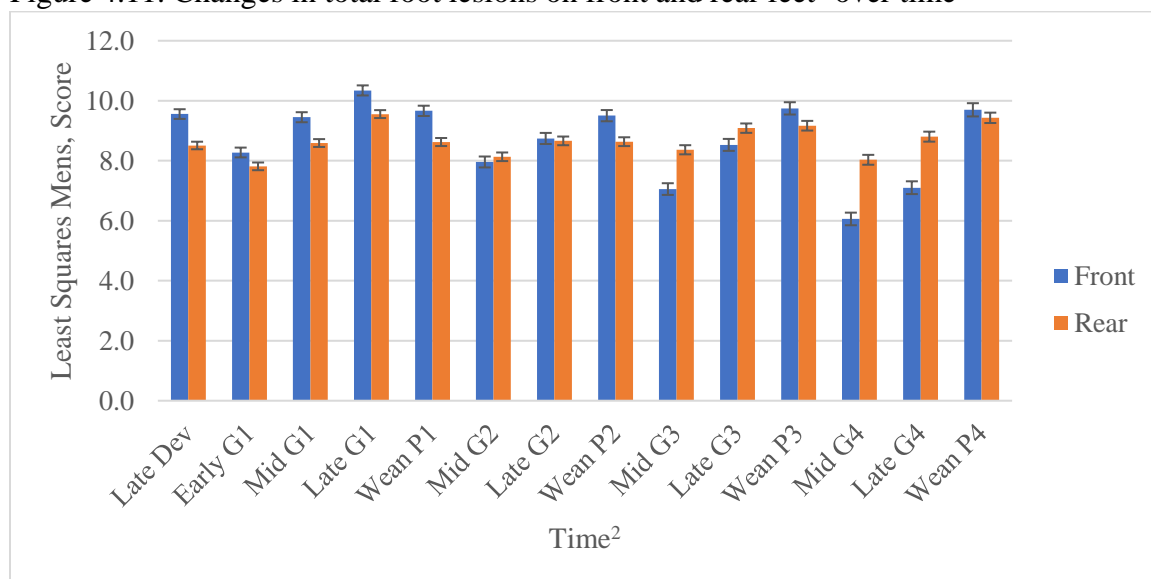


<sup>1</sup>Time of trait scoring. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Based on the fit of Cox proportional hazards models, some associations were identified between conformation and reproductive longevity as presently defined (Table 4.1). Body depth at the shoulder at wean P1, BDF and HS in late dev, and HF at both early and late dev were significantly associated with life on test ( $P < 0.05$ ), while HS and HF at mid G1 were approaching significance ( $P < 0.1$ ). Shallower body depth and taller height were associated with reduced life on test. An association was present between TIOR at mid G1 and life on test ( $P < 0.01$ ) in which sows that were more “toed out” had decreased reproductive longevity (Table 4.1). Conversely, we did not observe effects of TIOF at any time point tested on reproductive longevity ( $P > 0.1$ ). Some influence of foot

lesions was observed on reproductive longevity. Total lesion scores on the rear feet at mid G1 and HSC at wean P1 were significant sources of variation for life on test ( $P < 0.05$ ), and HOE at late dev was approaching significance ( $P < 0.1$ ). As expected, greater foot lesion scores were associated with decreased life on test in all cases.

Figure 4.11. Changes in total foot lesions on front and rear feet<sup>1</sup> over time



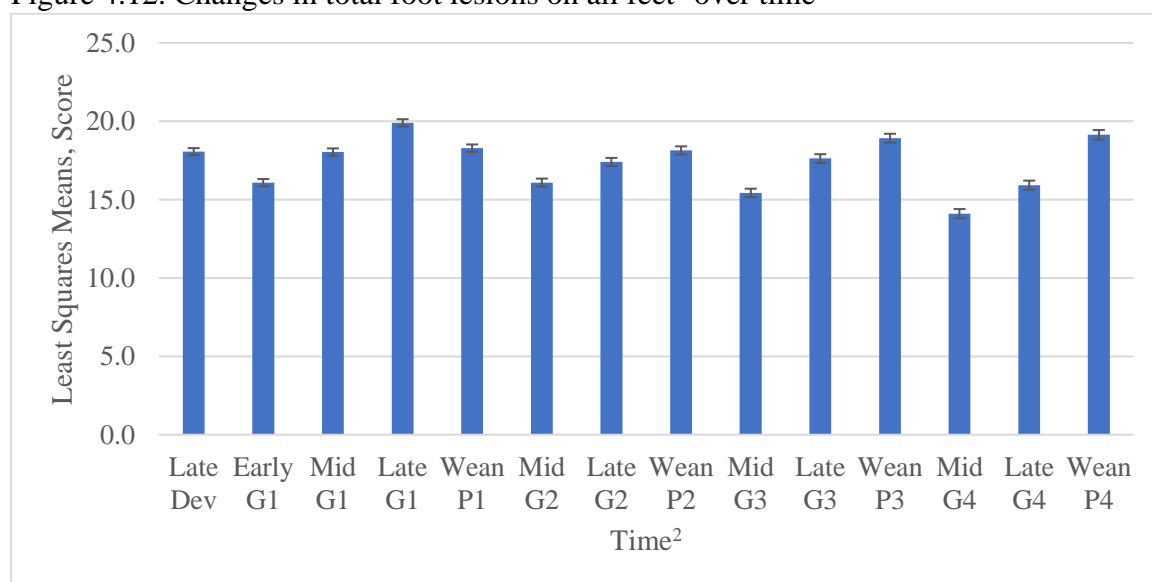
<sup>1</sup>Front = sum of heel overgrowth and erosion, heel-sole crack, and white line crack scores on the front feet, Rear = sum of heel overgrowth and erosion, heel-sole crack, and white line crack scores on the rear feet

<sup>2</sup>Time of trait scoring. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Knee, hock, and pastern angles were not significant sources of variation for life on test when linear effects were tested ( $P > 0.1$ ). However, KA at wean P1, FP in early dev, and RP at mid G1 were approaching significance ( $P < 0.1$ ). Softer (smaller) knee and rear pastern angles and straighter (larger) front pastern angles were associated with increased culling hazard. These traits are expected to have intermediate optimums, and no associations would be detected if both high and low trait values were detrimental to

reproductive longevity. Therefore, Cox proportional hazards models were fit with quadratic knee, hock, and pastern angle effects (Table 4.2). The quadratic effect of KA at early and late dev and FP at wean P1 were significant sources of variation for life on test ( $P < 0.05$ ). The quadratic effect of HA at mid G1 was approaching significance ( $P < 0.1$ ). As expected, small and large KA and HA values resulted in increased culling hazard. However, middle values of FP increased culling hazard.

Figure 4.12. Changes in total foot lesions on all feet<sup>1</sup> over time



<sup>1</sup>Sum of heel overgrowth and erosion, heel-sole crack, and white line crack scores on all feet

<sup>2</sup>Time of trait scoring. Late Dev = near the end of the development period at 206 days of age, Early G1 = day 30 of first gestation, Mid G1 = day 58 of first gestation, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Mid G2 = day 58 of second gestation, Late G2 = day 99 of second gestation, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Late G3 = day 99 of third gestation, Wean P3 = weaning of parity 3, Mid G4 = day 58 of fourth gestation, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

## 4.5 Discussion

Body size traits exhibited rapid growth during development, then slower growth occurred during each gestation. The small decreases in body depth observed at weaning were unsurprising as the growing litter was expected to cause body depth to increase throughout gestation and then decrease after farrowing. Decreases in body length and

height at weaning are less intuitive but could be related to weight loss and other physiological processes that occur during lactation (Farmer, 2014). Decreases in height could also be associated with decreases in pastern angles which occurred at weaning each parity.

Table 4.1. Hazard function estimates, p-values, and ratios for conformation traits influencing sow reproductive longevity<sup>1</sup>

<b>Trait<sup>2</sup></b>	<b>Time<sup>3</sup></b>	<b>Parameter Estimate</b>	<b>Chi-Square P-value</b>	<b>Hazard Ratio</b>
<b>BDS</b>	Wean P1	-0.1824	0.034	0.833
<b>BDF</b>	Late Dev	-0.2013	0.046	0.818
<b>HS</b>	Late Dev	0.1129	0.034	1.12
<b>HS</b>	Mid G1	0.1096	0.08	1.116
<b>HF</b>	Early Dev	0.1135	0.012	1.12
<b>HF</b>	Late Dev	0.1322	0.021	1.141
<b>HF</b>	Mid G1	0.0964	0.095	1.101
<b>KA</b>	Wean P1	-0.0212	0.099	0.979
<b>FP</b>	Early Dev	0.0195	0.059	1.02
<b>RP</b>	Mid G1	-0.0204	0.076	0.98
<b>TIOR</b>	Mid G1	-0.0376	0.002	0.963
<b>HOE</b>	Late Dev	0.0598	0.097	1.062
<b>HSC</b>	Wean P1	0.1003	0.029	1.106
<b>Rear</b>	Mid G1	0.0712	0.037	1.074

<sup>1</sup>Reproductive longevity defined as life on test, calculated as the number of days between the start of development at 112 days of age and culling

<sup>2</sup>BDS = body depth at the shoulder, BDF = body depth at the flank, HS = height at the shoulder, HF = height at the flank, KA = knee angle, FP = front pastern angle, RP = rear pastern angle, TIOR = foot directional position (i.e., toed in or out) of the rear foot, HOE = heel overgrowth and erosion, HSC = heel-sole crack, Rear = sum of all foot scores on rear feet

<sup>3</sup>Time of trait measurement or scoring. Wean P1 = weaning of parity 1, Late Dev = near the end of the development period at 206 days of age, Mid G1 = day 58 of first gestation, Early Dev = near the beginning of the development period at 112 days of age

Knee and pastern angles decreased over time, with the largest decreases occurring during development and between late gestation and weaning each parity. Large knee angles indicate straight or buck knees, which are undesirable and can lead to lameness. It is still advisable to cull all gilts with buck knees and very straight knees. However, a gilt

Table 4.2. Hazard function estimates, p-values, and ratios for conformation traits with quadratic association with sow reproductive longevity<sup>1</sup>

<b>Trait<sup>2</sup></b>	<b>Time<sup>3</sup></b>	<b>Parameter Estimate</b>	<b>Chi-Square P-value</b>	<b>Hazard Ratio</b>
<b>KA</b>	Early Dev	-0.2561	0.002	0.774
<b>KA squared</b>	Early Dev	0.0008	0.002	1.001
<b>KA</b>	Late Dev	-0.405	0.036	0.667
<b>KA squared</b>	Late Dev	0.0013	0.031	1.001
<b>HA</b>	Mid G1	-0.6422	0.064	0.526
<b>HA squared</b>	Mid G1	0.0022	0.065	1.002
<b>FP</b>	Wean P1	0.3563	0.043	1.428
<b>FP squared</b>	Wean P1	-0.0032	0.041	0.997

<sup>1</sup>Reproductive longevity defined as life on test, calculated as the number of days between the start of development and culling

<sup>2</sup>KA = knee angle, HA = hock angle, FP = front pastern angle

<sup>3</sup>Time of trait measurement or scoring. Early Dev = near the beginning of development period at 112 days of age, Late Dev = near the end of the development period at 206 days of age, Mid G1 = day 58 of first gestation, Wean P1 = weaning of parity 1

that has knees that are straighter than average but not extreme may not develop knee-related conformation issues as the knee angle may decrease over time into the acceptable range. Conversely, gilts that already have ample knee flex and small knee angles at the time of selection may develop problems later in life if knee angle continues to decrease. Too much knee curvature is also a potential problem, though typically considered less severe. Intermediate pastern angles are generally considered most desirable, while larger angles (straight pasterns) are considered more detrimental than smaller angles (weak pasterns). As with KA, it should still be recommended to cull animals with very straight pasterns when selecting replacement gilts. However, above average pasterns may be acceptable for selection as they may develop more flex over time, and particularly weak pasterns at the time of selection may be more detrimental than previously thought should the angles continue to decrease. Decreased knee and pastern angles, particularly around weaning, could be a consequence of increased joint laxity resulting from the physiological processes of gestation, parturition, and lactation. Joint laxity has been



shown to increase in human women during pregnancy and post-parturition (Schauberger et al., 1996). Measurements of knee laxity were greatest two to six weeks post-parturition, while elbow measurements reached the highest point during the second trimester (Schauberger et al., 1996). No changes in laxity within the second half of pregnancy were reported by Dumas and Reid (1997), but knee ligaments showed decreased laxity by four months postpartum. Furthermore, laxity of metacarpophalangeal extension increased in women in their second or greater pregnancy compared to women in their first pregnancy (Calguneri et al., 1982). Sow joints in the present study followed a similar trend of changes in laxity as those reported in humans.

Stock et al. (2018) assessed knee, hock, and pastern angles in gilts at 150 days of age and after their first parity at  $3.9 \pm 2.5$  weeks of second gestation using similar objective measurements to those used in the present study. They also found that knee, front pastern, and rear pastern angles decreased over time. However, Stock et al. (2018) reported an increase in hock angle, whereas in the present study, only small fluctuations that did not follow a clear pattern over time were observed. Knee angle decreased as gestation age increased in Stock et al. (2018), which agrees with the present results. de Sevilla et al. (2009) reported increased prevalence of sickle-hocked legs between six months of age and first farrowing and between first farrowing and second farrowing in both Large White and Landrace. This would correspond to decreased hock angle, which is not in agreement with Stock et al. (2018) or the present study. Incidence of plantigradism increased over time in both breeds (de Sevilla et al., 2009), which would correspond to small pastern angles. In the present study and that of Stock et al. (2018), pastern angles decreased over time but the incidence of pastern angles that would be

considered plantigrade was not assessed. Despite increased incidence of plantigradism, there was also an increase in straight pasterns in Landrace over time (de Sevilla et al., 2009), which the present study and Stock et al. (2018) did not observe. Incidence of splay-footed increased from six months of age to after first farrowing, but not between first and second farrowing in both Large White and Landrace (de Sevilla et al., 2009). This agrees with directional position of the front foot observed in the present study but not the rear foot.

Rump slope was steepest at mid and late development and at weaning each parity. Steeper rump slope is generally considered undesirable as it can result in the rear legs being positioned too far under the sow, weak pasterns, and unfavorable shifts in weight distribution (Wilson, 2021). Increased rump slope may be a result of the physiological processes involved in parturition and lactation with recovery occurring once these stressors have passed, though the exact mechanism driving these changes is uncertain. As foot directional position (toed in or out traits) generally followed a pattern corresponding to the stage of the gestational cycle, it is likely that the physiological processes associated with gestation and lactation play a role. Changes in joint laxity (Calguneri et al., 1982; Schauburger et al., 1996; Dumas and Reid, 1997) and hoof biomechanical and structural properties (Knott et al., 2007) associated with pregnancy and parturition may influence foot directional positioning; however, it is unclear why these processes would have different effects in the front and rear feet as observed in the present study.

The highest HOE and HSC scores occurred at weaning, while WL tended to be highest in G1. Accordingly, the lowest total front and all foot scores tended to occur during gestation in later parities. Total rear foot scores exhibited less fluctuation over

time than total front and all foot scores. Farrowing stall flooring may have contributed to increased HOE, HSC, and total foot lesions at weaning as increased foot lesion scores in non-lactating, open sows housed in farrowing stalls was observed in a preliminary study (Trenhaile-Grannemann, unpublished data). While additional research is needed to confirm this effect, different floor types have been shown to influence severity of foot lesions in sows (Calderón Díaz et al., 2014). Physiological changes resulting from parturition and lactation may still play a role. Sole lesion scores taken between two weeks prior to parturition and at 12 weeks of lactation were increased in pregnant and lactating dairy cows compared to maiden cows (Knott et al., 2007). Further inspection of biomechanical properties and structure within the foot revealed other changes that decreased the structural integrity and supportive ability of the foot in pregnant and lactating compared to maiden cows; these included elevated compounds in connective tissue that increase elastin in the corium, increased hoof laxity, and alterations to the angle of the laminae (Knott et al., 2007). Pen housing had an unfavorable effect on all foot lesion types (chapter 3), and these effects were more consistent across cohorts for WL than for other lesion types. Increased WL severity prior to wean P1 is likely due to all gilts being housed in pens during development and half being housed in pens during G1, while all sows were housed in stalls after P1 weaning.

Favorable associations between life on test and increased body depth and decreased height were identified from the fit of Cox proportional hazard models. Few other studies have assessed the effect of body size on reproductive longevity. However, genetic associations between subjectively scored body length and six definitions of longevity and lifetime productivity traits were reported in which longer body length was

unfavorable; however, no associations between body depth and longevity traits were found (Nikkilä et al., 2013). Conversely, subjectively scored body length and height were not genetically correlated to stayability in López-Serrano et al. (2000). Negative effects of height observed in the present study and body length in Nikkilä et al. (2013) could be due increased sow size because of genetic selection programs emphasizing growth combined with facilities that were built to house smaller sows. Marchant and Broom (1996) reported sows with greater body length and height required more time to lay down within the confines of a stall. However, no association was present between body size and time to lay down in a pen setting, suggesting stall size may be inadequate for larger sows (Marchant and Broom, 1996).

Rear feet with increased “toed out” directional positioning at mid G1 were associated with increased removal hazard. de Sevilla et al. (2008) reported the presence of splayed feet scored as binary traits at six months of age, 100 kg BW, and after first and second parturitions increased culling hazard in Duroc but not Large White or Landrace sows. Nikkilä et al. (2013) reported genetic associations between subjectively scored front legs turned at 190 d of age and longevity in which slight deviations out were favorable; however, this is opposite of expected. Correlations between the directional positioning of the rear legs and longevity were not significantly different from zero (Nikkilä et al., 2013).

Increased foot lesion severity resulted in increased culling hazard, particularly HSC and rear foot lesions during G1. Severe foot lesions can cause pain, which can lead to abnormal posture (KilBride et al., 2010), abnormal gait (Jørgensen, 2000), and lameness (Jørgensen, 2000). Presence of lesions on the hind feet were associated with

lameness and slipping while lying down (Bonde et al., 2004). Some lesion types may be more associated with lameness than others. White line cracks were significantly associated with lameness, but other lesion types did not reach significance in Anil et al. (2007). However, in the present study, HSC had the strongest association with life on test, and there were marginal effects of HOE on life on test. Total lesions on the rear feet were associated with life on test, while total lesions on the front feet were not. This is somewhat unexpected because the front feet bear a higher proportion of weight than the rear feet (Sun et al., 2011; Pluym et al., 2013). However, lesion scores on the rear feet did not change over time as much as the front feet, so the rear feet could have a greater effect on reproductive longevity because they do not recover from severe lesions as quickly as the front feet.

Marginal linear associations were identified between life on test and KA, FP, and RP at wean P1, early dev, and mid G1, respectively. Both large and small values for these traits are expected to be detrimental, but large values are expected to be more detrimental than small values. This was true for FP, but not for KA and RP. Since KA and RP decreased over time and did not come close to significance until wean P1 or mid G1, respectively, it is possible that some gilts with straight KA or RP either were already culled or had angle changes to become more ideal. Additionally, smaller rear pastern angles may be associated with sows standing with their rear legs too far under their bodies, which would affect weight distribution and gait. This could lead to lameness and make softer rear pasterns more problematic than straight pasterns. Sows that stand too far under on their rear legs would be expected to have smaller hock angles as well, but the impact on HA may have been smaller than RP as it was not significantly associated with

life on test. Quadratic associations between life on test and knee and hock angles aligned more closely with expectations as both large and small trait values increased culling hazard. However, the opposite was true for the quadratic association between FP and life on test. It is likely that the significant quadratic in this case may have been driven by a few outliers and should be interpreted with caution. In other studies, there was limited success identifying associations between subjectively scored leg angles and reproductive longevity. Genetic correlations between buck knees at 190 days of age and six longevity and lifetime prolificacy traits were not significantly different from zero (Nikkilä et al., 2013). de Sevilla et al. (2008) reported no effect of binary-scored sickle-hocks on removal hazard in Duroc, Large White, or Landrace sows in a combined analysis with scores at four time points from six months of age to P2 weaning. However, Nikkilä et al. (2013) reported significant genetic correlations indicating less upright rear legs were associated with increased lifetime piglets born alive per day of life and percent productive days. de Sevilla et al. (2008) reported the presence of plantigradism increased removal hazard in Duroc and Large White and approached significance in Landrace, while straight pasterns increased removal hazard in Large White only. Neither front nor rear pastern posture at 190 days of age had genetic correlations significantly different from zero with the six longevity and lifetime productivity traits analyzed in Nikkilä et al. (2013). However, it was expected that more associations would be identified in this work by using an objective measurement system compared to subjective scores. In the present study, culling was only performed when lameness and conformation problems became a welfare issue for the sow, whereas culling criteria is likely less lenient on commercial farms. It may be possible that some conformation defects are not as detrimental to a

sows' wellbeing and reproductive longevity as previously thought, and if given the chance, sows that have structural characteristics that are traditionally considered undesirable may have acceptable performance and reproductive longevity. It is also possible that additional care and attention could have helped these sows maintain production as the facility in which this research was conducted had fewer animals per caretaker when compared to commercial farms. However, despite lenience on conformation, our experimental protocols had stricter culling criteria compared to most commercial farms for some reproductive traits as sows were only allowed ten days to express estrus post-weaning and were not given second chances to conceive and farrow a litter. Therefore, sows with poor conformation were able to maintain production without markedly increased non-productive days. Culling was not performed for small litter size or poor lactation performance unless the entire litter was lost, so it is possible that poor conformation could negatively influence these traits.

Significant associations between life on test and BDS, TIOR, HSC, and total rear foot lesions were present after the time of selection. Further research is needed to determine if foot lesions assessed prior to selection are correlated with foot lesions during G1 and could be used as an indicator for future foot lesion and, consequently, reproductive longevity issues. Moreover, the associations explored here are purely phenotypic; genetic correlations between conformation traits and reproductive longevity must be assessed to inform selection decisions in the context of a breeding program. However, the present results are useful to inform selection of commercial sows.

## 4.6 Conclusions

Changes over time were observed for all conformation traits. Knee, front, and rear pastern angles decreased by 10.3, 5.7, and 7.8 degrees, respectively, between early development and P4 weaning, with the largest decreases observed during development and at weaning each parity. No overall changes over time were observed for hock angle and rump slope, but significant fluctuations were present. Rump slope tended to be the greatest in middle and late development and at weaning, while hock angle fluctuations were relatively small. The front foot tended to be most “toed out” at weaning while the rear foot tended to be the most straightforward at weaning. Foot lesions were most severe at weaning. Body size increased rapidly during development, with slower growth continuing during gestation throughout the study period. Increased height and decreased body depth were detrimental to reproductive longevity. Sows that were more “toed out” at mid G1 had an increased risk of removal, and more severe foot lesions were associated with reduced life on test, particularly on the rear feet during G1. Quadratic effects of knee and front pastern angles on reproductive longevity were identified. Both low and high knee angles during development were detrimental to reproductive longevity, but intermediate pastern angles at wean P1 surprisingly increased culling risk. Some conformation defects may not be as detrimental to reproductive longevity as previously thought. Changes over time may be worth consideration when selecting replacement gilts. Tall and shallow-bodied gilts and gilts with buck knees or very soft knees should not be selected. Rear foot position and foot lesions become important for reproductive longevity after selection has already occurred; more work is needed to identify predictors for future values of these traits at the time of selection.



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## **CHAPTER 5: GENETIC PARAMETERS OF OBJECTIVELY MEASURED CONFORMATION TRAITS AND FOOT LESIONS EVALUATED AT 16 TIME POINTS BETWEEN 112 DAYS OF AGE AND PARITY 4 WEANING IN SOWS**

### **5.1 Abstract**

Sow ( $n = 622$ ) conformation traits were evaluated at 16 time points between 112 days of age and weaning of parity 4 to estimate heritability and explore the genetic parameters of conformation traits throughout sow productive life. Body length, body depth at the shoulder and flank, height at the shoulder and flank, knee angle, hock angle, front and rear pastern angles, rump slope, and front and rear foot directional position (i.e., toed in or out) were objectively measured. Three types of foot lesions, heel overgrowth and erosion, heel-sole crack, and white line crack, were scored on a 4-point scale and summed across feet to generate foot scores for each lesion type and total lesion scores for front, rear, and all feet. Heritability was estimated for each trait at each time point using animal models. A subset of time points ( $n = 8$ ) were utilized in bivariate models to estimate genetic correlations between each pairwise combination. Body size traits, rump slope, heel overgrowth and erosion, and total lesion score on all feet were moderately heritable (median  $h^2 = 0.21$  to  $0.37$ ). Leg and foot angles, heel-sole crack, white line crack, and total front and rear lesion score were lowly heritable (median  $h^2 = 0.11$  to  $0.19$ ). Genetic correlations between time points of body length and rump slope were high ( $\geq 0.8$ ) for 23 of the 28 pairwise combinations of time points tested. Height at the shoulder and flank and hock angle had high genetic correlations ( $\geq 0.8$ ) between time points after breeding. For body depth, knee angle, and pastern angles, genetic correlations were lower and standard errors were higher in pairwise comparisons involving parity 4

weaning. Late fourth gestation also had lower genetic correlations and higher standard errors for body depth. However, body size traits, leg angles, and rump slope appear to be the same trait genetically between most time points evaluated. Genetic correlations for foot directional position traits and foot lesions had high standard errors with many genetic correlations below 0.8. The genetic determinism of these traits may differ over time. Experimental validation of genetic relationships with reproductive longevity, body size traits, leg angles, and rump slope could lead to incorporation of these traits in a breeding program to improve sow fitness, welfare, and farm profitability.

## **5.2 Introduction**

Genetic selection of conformation traits could be economically valuable to the swine industry through improved welfare, fitness, and performance. Lameness is one of the most common reasons for early removal of breeding females in several regions of the world (Mote et al., 2008; Segura-Correa et al., 2011; Zhao et al., 2015). Incorporation of conformation traits into a breeding program and selection index will result in more efficient genetic progress than truncation selection based on visual appraisal (Hazel and Lush, 1942). Furthermore, genetic correlations have been identified between conformation traits and sow reproductive longevity (López-Serrano et al., 2000; Nikkilä et al., 2013a; Le et al., 2016). Reproductive longevity is expressed late in life and is impractical to measure in nucleus herds. Correlations with indicator traits, such as conformation, are imperative to successfully select for increased reproductive longevity and fitness in a breeding program.

Most studies evaluating genetic parameters of conformation traits have used subjective scoring systems to evaluate conformation, often using traits that encompass

multiple aspects of conformation or focusing just on structural defects. Digital imaging offers a repeatable method of objective conformation trait measurement that can account for the full range of trait values (Stock et al., 2017). However, few heritability estimates of conformation traits evaluated using objective measurements have been reported (Stock et al., 2018). Furthermore, sow conformation has been shown to change throughout life (chapter 4). Genetic correlations between conformation measured at different points in life are necessary to determine if conformation traits are functionally the same from a genetic standpoint over time. However, few studies have evaluated conformation traits at multiple time points with any method (Stock et al., 2018).

Foot lesions are highly prevalent within sow herds, and 80 to 98 percent of sows were found to have at least one foot lesion (Anil et al., 2007; Ossent et al., 2010; Sasaki et al., 2015). Foot lesions can be painful and lead to lameness and poor animal welfare (Ossent et al., 2010). However, the genetic determinism of foot lesions in swine is yet to be explored. The objectives of this study were to estimate heritability of objectively measured conformation traits and foot lesions in sows and genetic correlations of these traits when evaluated at several time points throughout life.

## **5.3 Materials and Methods**

### **5.3.1 Animals**

All procedures involving animals were approved by the University of Nebraska Institutional Animal Care and Use Committee protocol number 1859. Gilts ( $n = 622$ ) were developed in five cohorts. Cohorts 1 and 2 were derived from Nebraska Index Line (Hsu and Johnson, 2014) dams that were parity 1 and 2, respectively. Cohorts 3 to 5 were

derived from dams that completed four parities. The same Nebraska Index Line sows were used to produce cohorts 1 and 2, while the dams used to produce cohorts 3 to 5 were unique to each specific cohort. Cohort 1 became the dams of cohort 4, and cohort 2 were the dams of cohort 5; the dams of cohort 3 were not utilized in this study. Commercial Landrace boars sired cohorts 1 and 2, and commercial Yorkshire boars sired cohorts 3 to 5. Each cohort was sired by 10 to 12 boars that were unique to each cohort, except for three boars that produced sows in both cohorts 1 and 2. Thirty-five to 45 dams were used to produce each cohort.

### **5.3.2 Management**

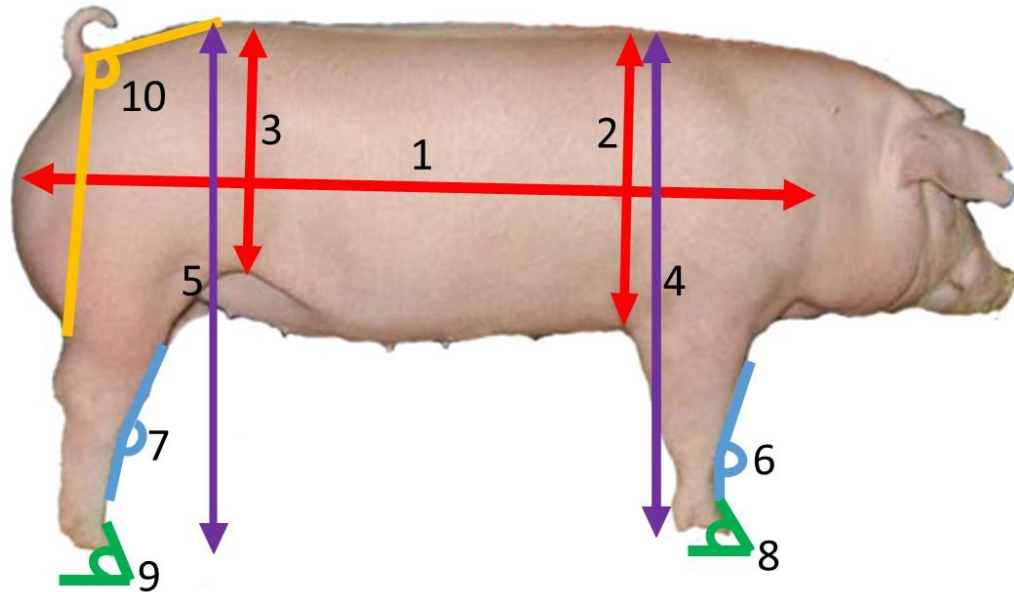
Sows were managed as described in chapter 3. Briefly, gilts were allocated to one of three developmental diets: a standard corn-soybean meal diet (CTRL), an energy restricted diet via inclusion of 40% soyhulls (RES) with similar amino acids and other nutrients as CTRL, and a diet with the same metabolizable energy as CTRL and same lysine to metabolizable energy ratio as RES (LYS). The different dietary treatments were fed during the developmental period from approximately 112 to 215 days of age. After the development period, all sows received the same standard gestation and lactation diets, formulated to meet or exceed NRC (2012) requirements.

During first gestation, gilts were allocated to pen or stall gestation housing, except in cohort 2 due to management constraints. After first gestation, all sows were housed in stalls. Sows remained in production through four parities and were culled only for reproductive failure and animal welfare reasons, such as severe sickness or lameness. Of the 622 gilts that began the experiment, 254 produced all four parities while 163 never

farrowed. Eighty-three, 63, and 59 sows were removed after producing 1, 2, and 3 parities, respectively.

### 5.3.3 Conformation Trait Data Collection

Figure 5.1. Side view conformation traits measured.



1 = body length (BL, cm), 2 = body depth at the shoulder (BDS, cm), 3 = body depth at the flank (BDF, cm), 4 = height at the shoulder (HS, cm), 5 = height at the flank (HF, cm), 6 = knee angle (KA, degrees), 7 = hock angle (HA, degrees), 8 = front pastern angle (FP, degrees), 9 = rear pastern angle (RP, degrees), 10 = rump slope (RS, degrees)

Collection of conformation trait phenotypes was described in chapter 2. Briefly, conformation data was collected at  $112.3 (\pm 4.3)$ ,  $167.1 (\pm 3.4)$ , and  $206.3 (\pm 6.4)$  days of age, at day  $30.2 (\pm 6.5)$  of first gestation (G), at  $58.4 (\pm 6.7)$  and  $98.9 (\pm 5.2)$  of G 1 to 4, and  $1.6 (\pm 1.9)$  days after weaning in parity (P) 1 to 4 (hereafter “early dev”, “mid dev”, “late dev”, “early G”, “mid G”, “late G”, and “wean P”). Five body size traits and five leg and body angles were measured from the side view (Figure 5.1). The five body size traits were body length (BL), body depth at the shoulder (BDS), body depth at the flank (BDF),



Figure 5.2. Foot directional positioning (i.e., toed in or out) angle measurement<sup>1</sup>



<sup>1</sup>Angles assessing directional position of foot (i.e., toed in or out) on the front (TIOF) and rear (TIOR) left feet, measured in degrees. Angles of 90 degrees indicate the foot is facing straight forward, while angles less than 90 degrees indicate the foot is “toed out” and angles greater than 90 degrees indicate the foot is “toed in”.

height at the shoulder (HS), and height at the flank (HF). Leg and body angles from the side view consisted of knee angle (KA), hock angle (HA), front and rear pastern angle (FP and RP, respectively), and rump slope (RS). Images of the feet from the front view were used to assess directional positioning of each foot (i.e., toed in or out) via an angle beginning in the center of the toes at the point of divergence, coming to a point halfway between the toe tips, and going straight inward (Figure 5.2). These angles were measured on the front (TIOF) and rear (TIOR) left feet. Foot lesions of heel overgrowth and erosion (HOE), heel-sole cracks (HSC), and white line cracks (WL) were scored on a 4-point scale (FeetFirst® Lesion Scoring Guide, Zinpro Corporation, Eden Prairie, MN) on all four feet. Scores of each lesion type were summed across feet, and scores of all lesion types were summed to create total lesion scores for the front, rear, and all feet. Foot lesions were phenotyped at all time points starting at late dev in cohorts 3 to 5 and late G1 in cohorts 1 and 2; the exceptions were wean P1, mid G2, and mid G3 in cohort 1 and

mid G2 in cohort 2. Side view trait phenotypes were obtained at all time points, and foot directional position trait phenotypes were obtained beginning with early G1.

#### **5.3.4 Statistical Analysis**

Heritability of each conformation trait at each time point was estimated fitting an animal model in ASReml v.4.1 (Gilmour et al., 2014). The dataset contained two to three sets of measurements taken for each trait at each time point as reported in chapter 2.

Fixed effects were cohort, developmental diet, housing system during first gestation, and two-way interactions of developmental diet with both cohort and first gestation housing system. Effects involving first gestation housing system were excluded for conformation traits measured prior to breeding. Random animal genetic and permanent environment and evaluator effects were fitted. The pedigree file contained sires, dams, and maternal grand-dams of all animals and maternal great-grand-dams of cohorts 4 and 5.

To assess whether genetic determinism of conformation traits is the same throughout life, a series of bivariate models were implemented between the same measurement taken at different time points. All pairwise combinations of late dev, weaning each parity, late G1, mid G3, and late G4 were modeled to assess the genetic correlation between them. The bivariate models included the same fixed and random effects as the univariate models described above. Variance components estimated from the univariate models were used as starting values for bivariate models. Starting values for covariance components were estimated assuming correlations of 0.8 for animal genetic and evaluator effects and 0.2 for animal permanent environment and residual effects as these were near the average correlations obtained from the model fit.

## 5.4 Results and Discussion

### 5.4.1 Heritability of Conformation Traits

Heritability estimates (Table 5.1) were low to moderate. Across all traits and time points, the minimum heritability was 0, and the maximum heritability was 0.5. Within each trait, the range of heritability estimates obtained between time points was large (difference between the smallest and largest heritability estimate of 0.18 to 0.40). It is expected that the true heritability of each trait is near the median of estimates obtained across time points and that extreme values in the distribution are inaccurate due to low numbers of individuals. Therefore, median and lower and upper quartile heritability values were reported in table 5.1. Median and lower and upper quartile values for standard errors are also reported to provide a scope of the range of these values for individual time points. Most heritability estimates above the lower quartile were at least two times their standard errors, especially for moderately heritable objectively measured conformation traits. Standard errors were relatively higher for subjectively scored foot lesions, especially for the lowly heritable traits of HSC and total rear foot lesions. Even though heritability estimates were not as low for total lesion scores on the front feet and all feet compared to HSC and total rear lesions, standard errors were of similar size to their corresponding heritability estimates at most time points for these composite foot lesion traits.

Body size traits were moderately heritable (Table 5.1). Body depth and height had higher heritability estimates when they were measured at the shoulder compared to when they were measured at the flank. Heritability estimates of body length and body depth

Table 5.1. Median and lower and upper quartile heritability estimates and standard errors across all time points of conformation traits. These traits were evaluated at 16 time points between 112 days of age and parity 4 weaning.

<b>Trait<sup>3</sup></b>	<b>Heritability<sup>1</sup></b>			<b>Standard Error<sup>2</sup></b>		
	Median <sup>4</sup>	Lower Quartile <sup>5</sup>	Upper Quartile <sup>6</sup>	Median <sup>4</sup>	Lower Quartile <sup>5</sup>	Upper Quartile <sup>6</sup>
<b>BL</b>	0.21	0.16	0.27	0.09	0.08	0.10
<b>BDS</b>	0.25	0.19	0.36	0.10	0.08	0.11
<b>BDF</b>	0.23	0.16	0.32	0.09	0.08	0.10
<b>HS</b>	0.37	0.27	0.40	0.10	0.09	0.12
<b>HF</b>	0.26	0.23	0.38	0.10	0.09	0.12
<b>KA</b>	0.17	0.14	0.20	0.07	0.07	0.08
<b>HA</b>	0.13	0.11	0.17	0.06	0.06	0.08
<b>FP</b>	0.15	0.10	0.25	0.06	0.05	0.10
<b>RP</b>	0.15	0.12	0.26	0.08	0.06	0.10
<b>RS</b>	0.23	0.19	0.33	0.09	0.07	0.11
<b>TIOF</b>	0.19	0.10	0.29	0.09	0.07	0.12
<b>TIOR</b>	0.16	0.10	0.19	0.11	0.10	0.12
<b>HOE</b>	0.30	0.24	0.41	0.13	0.11	0.14
<b>HSC</b>	0.11	0.03	0.18	0.10	0.06	0.11
<b>WL</b>	0.15	0.13	0.29	0.12	0.10	0.14
<b>Front</b>	0.17	0.09	0.25	0.11	0.10	0.12
<b>Rear</b>	0.08	0.04	0.24	0.11	0.09	0.12
<b>All</b>	0.21	0.10	0.32	0.12	0.11	0.13

<sup>1</sup>Heritability estimated from univariate models for each trait and time point

<sup>2</sup>Standard error of heritability estimates obtained with univariate models for each trait and time point

<sup>3</sup>BL = body length, BDS = body depth at the shoulder, BDF = body depth at the flank, HS = height at the shoulder, HF = height at the flank, KA = knee angle, HA = hock angle, FP = front pastern angle, RP = rear pastern angle, RS = rump slope, TIOF = directional position (i.e., toed in or out) of the front left foot, TIOR = directional position (i.e., toed in or out) of the rear left foot, HOE = heel overgrowth and erosion, HSC = heel-sole crack, WL = white line crack, Front = total score of all lesions on front feet, Rear = total score of all lesions on rear feet, All = total score of all lesions on all feet. Body size (BL, BDS, BDF, HS, and HF) and foot directional positioning (TIOF, TIOR) traits were objectively measured by two evaluators. Leg and body angles (KA, HA, FP, RP, and RS) were objectively measured by three evaluators. Foot lesions (HOE, HSC, WL, Front, Rear, All) were subjectively scored by one evaluator.

<sup>4</sup>Median value of heritability estimates and standard errors from individual analyses of 16 time points

<sup>5</sup>Lower quartile of heritability estimates and standard errors from individual analyses of 16 time points

<sup>6</sup>Upper quartile of heritability estimates and standard errors from individual analyses of 16 time points

subjectively scored on a 9-point scale in gilts at 124 kg of body weight (Nikkilä et al., 2013b) are closer to the upper quartile of the estimates in the present study but are within a standard error of the median presented here. López-Serrano et al. (2000) reported lower heritability values for body length and height subjectively scored on a 9-point scale at the time of gilt selection at 105 kg; those estimates are similar to the lower quartile of body length heritability estimates and below the lower quartile of height heritability estimates in the present study. Fukawa et al. (2001) reported heritability estimates for body length and height at the shoulder measured in Duroc pigs at 90 kg that are similar to the upper quartile of BL heritability estimates and lower quartile of HS heritability estimates in the present study.

Leg and foot directional position angles had lower heritability compared to body size traits (Table 5.1). For most traits, the median heritability would be considered lowly heritable, but the upper quartile reached the moderate range. Heritability estimates for KA, HA, FP, and RP that were objectively measured with the same procedure at selection (150 days of age) and post first parity were reported by Stock et al. (2018). Similar to the present study, heritability estimates were variable between the two time points (Stock et al., 2018). Heritability estimates from the former study were generally higher than median heritability estimates but similar to upper quartile heritability estimates in the present study. Heritability of hock and pastern angles were slightly above upper quartile estimates in the present study when scored on a 9-point scale (Nikkilä et al., 2013b). However, the heritability estimate of buck knees scored on a 9-point scale (Nikkilä et al., 2013b) was just below the lower quartile of KA heritability estimates in the present study. Heritability estimates were generally lower for most joints in studies that focused

on defects and used subjective scales with fewer categories (Serenius et al., 2001; de Sevilla et al., 2009). Heritability estimates for subjectively scored foot turned in (Nikkilä et al., 2013b) are similar to TIOF lower quartile heritability estimates and TIOR upper quartile heritability estimates in the present study. Foot directional positioning heritability estimates in the present study are similar to heritability estimates for splay-footed in de Sevilla et al. (2009) and higher than heritability estimates for front legs turned out in Serenius et al. (2001). Rump slope was moderately heritable (Table 5.1). Heritability for subjectively scored hip structure (Nikkilä et al., 2013b) was similar to the RS lower quartile heritability estimates in the present study.

Heritability estimates varied between foot lesion types (Table 5.1). Heel overgrowth and erosion was moderately heritable, HSC was lowly heritable, and WL had low to moderate heritability. The lower HSC heritability was likely due in part to lower incidence and severity of HSC lesions compared to HOE and WL. Across time points, the average HSC score was 3.9 compared to average scores 6.7 for both HOE and WL on a scale of 0 to 12. Despite having the same average score, greater heritability estimates were obtained for HOE when compared to WL. Total lesion scores on the front, rear, and all feet were lowly to moderately heritable, with large ranges between the lower and upper quartiles, particularly for total lesion score on all feet. To our knowledge, this is the first study to estimate heritability of foot lesions in pigs. However, the genetics of foot lesions has been studied more extensively in dairy cattle, and heritability estimates for foot lesions in swine in the present study are similar to those reported in dairy cattle (van der Waaij et al., 2005; Onyiro et al., 2008; Laursen et al., 2009; van der Linde et al., 2010; Buch et al., 2011; Chapinal et al., 2013; Oberbauer et al., 2013; Schöpke et al.,

2013; van der Spek et al., 2013; Dhakal et al., 2015; Schöpke et al., 2015; Malchiodi et al., 2017).

## 5.4.2 Genetic Correlations Across Time

Table 5.2. Genetic correlations<sup>1</sup> between body length (upper diagonal) and rump slope (lower diagonal) objectively measured<sup>2</sup> at multiple time points<sup>3</sup>.

	<b>Late Dev</b>	<b>Late G1</b>	<b>Wean P1</b>	<b>Wean P2</b>	<b>Mid G3</b>	<b>Wean P3</b>	<b>Late G4</b>	<b>Wean P4</b>
<b>Late Dev</b>		0.99 (± 0.29)	0.89 (± 0.33)	0.93 (± 0.29)	0.95 (± 0.33)	0.93 (± 0.46)	0.86 (± 0.46)	0.99 (± 0.46)
<b>Late G1</b>	0.81 (± 0.17)		0.89 (± 0.13)	0.66 (± 0.18)	0.81 (± 0.16)	0.87 (± 0.19)	0.62 (± 0.23)	0.65 (± 0.21)
<b>Wean P1</b>	0.82 (± 0.20)	0.88 (± 0.13)		0.89 (± 0.14)	0.95 (± 0.15)	0.93 (± 0.23)	1.00 (± 0.20)	0.89 (± 0.20)
<b>Wean P2</b>	0.84 (± 0.22)	0.79 (± 0.16)	0.99 (± 0.15)		0.91 (± 0.12)	0.88 (± 0.14)	0.78 (± 0.21)	0.50 (± 0.23)
<b>Mid G3</b>	0.67 (± 0.23)	0.78 (± 0.15)	0.99 (± 0.20)	0.89 (± 0.14)		0.98 (± 0.12)	0.91 (± 0.13)	0.84 (± 0.14)
<b>Wean P3</b>	1.00 (± 0.23)	0.82 (± 0.15)	0.95 (± 0.17)	0.93 (± 0.17)	0.99 (± 0.14)		0.94 (± 0.20)	0.97 (± 0.26)
<b>Late G4</b>	0.91 (± 0.17)	0.95 (± 0.14)	0.95 (± 0.15)	0.97 (± 0.14)	0.91 (± 0.14)	0.98 (± 0.15)		0.92 (± 0.17)
<b>Wean P4</b>	0.79 (± 0.23)	0.74 (± 0.18)	0.94 (± 0.21)	0.92 (± 0.18)	0.99 (± 0.14)	0.97 (± 0.14)	0.81 (± 0.19)	

<sup>1</sup>Genetic correlations estimated with pairwise bivariate animal models

<sup>2</sup>Body length and rump slope angle were objectively measured by two and three evaluators, respectively, on pictures of sows at each time point

<sup>3</sup>Late Dev = near the end of the development period at 206 days of age, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Wean P3 = weaning of parity 3, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Genetic correlations were estimated between measurements or scores of each trait evaluated at late dev, late G1, wean P1, wean P2, mid G3, wean P3, late G4, and wean P4 for a total of 28 pairwise genetic correlation estimates. Late dev was chosen because it was near the time gilts are typically selected, and weaning time points were chosen because most culling decisions are made at weaning. Both mid and late gestation time points were included because it was suspected that genetic correlations between time points at the same stage of the gestation cycle might be higher than correlations between

time points at different stages due to a cyclical pattern of change that follows the gestation cycle for many conformation traits (chapter 4). Genetic correlations between time points reveal whether the genetic determinism of the traits remain the same over time and if measurements or scores from different time points can be considered the same trait or not. Genetic correlations above 0.8 indicate that evaluations at different time points can potentially be considered the same trait, while genetic correlations below 0.8 indicate measurements or scores from different time points should be considered separate traits (Robertson, 1959).

Table 5.3. Genetic correlations<sup>1</sup> between height at the shoulder (upper diagonal) and height at the flank (lower diagonal) objectively measured<sup>2</sup> at multiple time points<sup>3</sup>.

	<b>Late Dev</b>	<b>Late G1</b>	<b>Wean P1</b>	<b>Wean P2</b>	<b>Mid G3</b>	<b>Wean P3</b>	<b>Late G4</b>	<b>Wean P4</b>
<b>Late Dev</b>		0.82 (± 0.17)	0.80 (± 0.19)	0.88 (± 0.20)	0.61 (± 0.25)	0.47 (± 0.30)	0.74 (± 0.24)	0.90 (± 0.28)
<b>Late G1</b>	0.95 (± 0.12)		0.95 (± 0.10)	0.97 (± 0.10)	1.00 (± 0.09)	0.98 (± 0.12)	0.96 (± 0.10)	0.92 (± 0.16)
<b>Wean P1</b>	0.64 (± 0.23)	0.98 (± 0.09)		0.97 (± 0.11)	0.99 (± 0.10)	0.93 (± 0.15)	0.97 (± 0.11)	DNC
<b>Wean P2</b>	0.77 (± 0.22)	0.97 (± 0.18)	0.92 (± 0.15)		0.97 (± 0.09)	0.95 (± 0.11)	0.99 (± 0.12)	0.94 (± 0.16)
<b>Mid G3</b>	0.70 (± 0.19)	0.87 (± 0.11)	0.96 (± 0.13)	0.79 (± 0.15)		0.83 (± 0.14)	0.95 (± 0.10)	0.99 (± 0.16)
<b>Wean P3</b>	0.25 (± 0.31)	0.90 (± 0.15)	0.69 (± 0.20)	0.97 (± 0.20)	0.81 (± 0.11)		0.98 (± 0.12)	0.95 (± 0.18)
<b>Late G4</b>	0.65 (± 0.26)	0.99 (± 0.13)	0.95 (± 0.16)	0.93 (± 0.18)	0.96 (± 0.10)	0.88 (± 0.15)		0.93 (± 0.16)
<b>Wean P4</b>	0.99 (± 0.32)	1.00 (± 0.18)	0.90 (± 0.24)	0.73 (± 0.25)	0.96 (± 0.13)	0.78 (± 0.19)	0.92 (± 0.19)	

<sup>1</sup>Genetic correlations estimated with pairwise bivariate animal models

<sup>2</sup>Height at the shoulder and flank were objectively measured by two evaluators on pictures of sows at each time point

<sup>3</sup>Late Dev = near the end of the development period at 206 days of age, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Wean P3 = weaning of parity 3, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Genetic correlations were above 0.8 for 23 of the 28 pairwise combinations of time points for both BL and RS (Table 5.2). All genetic correlation estimates were at



least three times their standard errors for RS, except late dev and mid G3. This time point combination had the lowest genetic correlation estimate at 0.67, while all other time point combinations had genetic correlations of 0.74 or greater. Most genetic correlation estimates for BL were also three times their standard errors. However, six genetic correlations were only two times their standard error estimate, and the standard error for late dev and late G4 was approaching the genetic correlation estimate. Genetic correlations for HS (Table 5.3) were all above 0.8, except three that involved late dev and one that did not converge between wean P1 and wean P4. All HS genetic correlation estimates that were above 0.8 were also at least three times greater than their standard errors.

Other body size traits (Tables 5.3 and 5.4) had more combinations of time points that did not reach the genetic correlation threshold of 0.8. Most time point combinations with genetic correlations below 0.8 involved late dev and wean P4, and genetic correlation estimates involving these time points often had higher standard errors than genetic correlation estimates not involving these time points. Gilts were still in the rapid growth phase at 206 days of age (Robison, 1976) when measurements from late dev were evaluated, and phenotypic changes in conformation occurred at a rapid rate throughout development (chapter 4). Furthermore, sows were removed throughout the study period, leaving wean P4 with the least data to estimate genetic parameters. Excluding these two time points, 13 of the 15 remaining BDF and HF pairwise genetic correlations were greater than 0.8, and nearly all were at least three times greater than their standard errors. Standard errors were large at late G4 for BDS. Excluding late dev, late G4, wean P4, and

a model which did not converge, eight out of nine remaining BDS pairwise genetic correlations were above 0.8 and all were three times their standard errors.

Table 5.4. Genetic correlations<sup>1</sup> between body depth at the shoulder (upper diagonal) and body depth at the flank (lower diagonal) objectively measured<sup>2</sup> at multiple time points<sup>3</sup>.

	<b>Late Dev</b>	<b>Late G1</b>	<b>Wean P1</b>	<b>Wean P2</b>	<b>Mid G3</b>	<b>Wean P3</b>	<b>Late G4</b>	<b>Wean P4</b>
<b>Late Dev</b>		0.75 (± 0.19)	0.80 (± 0.26)	0.63 (± 0.21)	0.42 (± 0.28)	0.08 (± 0.34)	0.93 (± 0.49)	0.87 (± 2.26)
<b>Late G1</b>	0.96 (± 0.13)		0.97 (± 0.12)	0.86 (± 0.12)	0.87 (± 0.13)	0.82 (± 0.18)	0.87 (± 2.64)	0.99 (± 0.49)
<b>Wean P1</b>	0.81 (± 0.22)	0.95 (± 0.18)		DNC	0.84 (± 0.20)	0.99 (± 0.22)	0.83 (± 0.83)	0.90 (± 2.22)
<b>Wean P2</b>	0.69 (± 0.28)	0.90 (± 0.24)	0.99 (± 0.23)		0.92 (± 0.10)	0.96 (± 0.11)	DNC	0.99 (± 0.39)
<b>Mid G3</b>	0.72 (± 0.21)	0.95 (± 0.15)	0.91 (± 0.28)	0.99 (± 0.19)		0.67 (± 0.21)	0.99 (± 0.36)	0.98 (± 0.45)
<b>Wean P3</b>	0.73 (± 0.20)	0.92 (± 0.19)	0.95 (± 0.19)	0.94 (± 0.22)	0.65 (± 0.21)		DNC	0.86 (± 0.43)
<b>Late G4</b>	0.99 (± 0.43)	0.94 (± 0.27)	0.95 (± 0.30)	0.95 (± 0.31)	0.89 (± 0.25)	0.58 (± 0.42)		DNC
<b>Wean P4</b>	0.94 (± 0.78)	0.96 (± 0.36)	0.98 (± 0.31)	0.61 (± 0.49)	0.95 (± 0.43)	0.91 (± 0.39)	0.39 (± 1.00)	

<sup>1</sup>Genetic correlations estimated with pairwise bivariate animal models

<sup>2</sup>Body depth at the shoulder and flank were objectively measured by two evaluators on pictures of sows at each time point

<sup>3</sup>Late Dev = near the end of the development period at 206 days of age, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Wean P3 = weaning of parity 3, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Likewise, late dev and wean P4 tended to be the time points with the lowest genetic correlations and highest standard errors for leg angle traits. When excluding these time points, all genetic correlations between time points for KA were at least 0.8 and three times their standard errors (Table 5.5). Wean P4 HA was highly genetically correlated to other time points with relatively low standard errors. Only two pairwise genetic correlations for HA were below 0.8 when late dev was excluded, and all but the lowest genetic correlation were at least three times their standard errors (Table 5.5).

Three pairwise genetic correlations involving wean G1 and late G4 were below 0.8 with

relatively high standard errors for FP, and the bivariate model for these time points did not converge (Table 5.6). However, all other genetic correlations were above 0.8, and most were three times their standard error, excluding late dev and wean P4. For RP, late dev and mid G3 had low genetic correlations with most other time points, while standard errors were relatively high for genetic correlations involving late dev, wean P2, and wean P4 (Table 5.6). Nevertheless, most RP genetic correlations exceeded 0.8.

Table 5.5. Genetic correlations<sup>1</sup> between knee angle (upper diagonal) and hock angle (lower diagonal) objectively measured<sup>2</sup> at multiple time points<sup>3</sup>.

	<b>Late Dev</b>	<b>Late G1</b>	<b>Wean P1</b>	<b>Wean P2</b>	<b>Mid G3</b>	<b>Wean P3</b>	<b>Late G4</b>	<b>Wean P4</b>
<b>Late Dev</b>		0.97 (± 0.16)	0.83 (± 0.13)	0.90 (± 0.21)	0.63 (± 0.23)	0.69 (± 0.23)	0.50 (± 0.24)	0.64 (± 0.26)
<b>Late G1</b>	0.86 (± 0.24)		0.97 (± 0.07)	0.93 (± 0.16)	0.99 (± 0.13)	0.90 (± 0.15)	0.87 (± 0.17)	0.67 (± 0.22)
<b>Wean P1</b>	0.70 (± 0.21)	0.73 (± 0.16)		1.00 (± 0.10)	0.89 (± 0.11)	0.91 (± 0.11)	0.80 (± 0.13)	0.75 (± 0.16)
<b>Wean P2</b>	0.39 (± 0.33)	0.83 (± 0.19)	0.95 (± 0.19)		0.96 (± 0.10)	0.86 (± 0.15)	0.97 (± 0.14)	0.81 (± 0.16)
<b>Mid G3</b>	0.96 (± 0.30)	1.00 (± 0.25)	0.95 (± 0.19)	0.94 (± 0.17)		0.95 (± 0.11)	0.98 (± 0.10)	0.77 (± 0.17)
<b>Wean P3</b>	0.58 (± 0.24)	0.57 (± 0.20)	0.95 (± 0.15)	0.97 (± 0.17)	0.94 (± 0.11)		0.99 (± 0.09)	0.92 (± 0.12)
<b>Late G4</b>	0.80 (± 0.30)	0.93 (± 0.27)	0.96 (± 0.15)	0.89 (± 0.24)	0.92 (± 0.24)	0.95 (± 0.16)		0.95 (± 0.14)
<b>Wean P4</b>	0.58 (± 0.34)	0.97 (± 0.24)	0.99 (± 0.18)	0.91 (± 0.24)	0.99 (± 0.19)	0.95 (± 0.12)	0.94 (± 0.22)	

<sup>1</sup>Genetic correlations estimated with pairwise bivariate animal models

<sup>2</sup>Knee and hock angle were objectively measured by three evaluators on pictures of sows at each time point

<sup>3</sup>Late Dev = near the end of the development period at 206 days of age, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Wean P3 = weaning of parity 3, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

While most genetic correlations were high for foot directional position (i.e., toed in or out) traits, standard errors were also high. Many standard errors were half their genetic correlation estimate or greater. Several foot directional position bivariate models were unable to reach convergence. The genetic variance was near zero for TIOF at wean

P1, which resulted in nonsensical parameter estimates. Four bivariate models involving early G1 and wean P4 of TIOR did not converge.

Table 5.6. Genetic correlations<sup>1</sup> between front pastern angle (upper diagonal) and rear pastern angle (lower diagonal) objectively measured<sup>2</sup> at multiple time points<sup>3</sup>.

	<b>Late Dev</b>	<b>Late G1</b>	<b>Wean P1</b>	<b>Wean P2</b>	<b>Mid G3</b>	<b>Wean P3</b>	<b>Late G4</b>	<b>Wean P4</b>
<b>Late Dev</b>		0.72 (± 0.22)	0.91 (± 0.27)	1.00 (± 0.33)	0.65 (± 0.24)	0.58 (± 0.30)	1.00 (± 0.31)	0.61 (± 0.29)
<b>Late G1</b>	0.98 (± 0.37)		0.94 (± 0.16)	0.90 (± 0.22)	0.84 (± 0.15)	0.95 (± 0.18)	0.62 (± 0.25)	0.43 (± 0.25)
<b>Wean P1</b>	0.95 (± 0.31)	0.89 (± 0.21)		0.90 (± 0.25)	0.71 (± 0.21)	0.72 (± 0.31)	DNC	0.60 (± 0.29)
<b>Wean P2</b>	0.63 (± 0.45)	1.00 (± 0.36)	0.88 (± 0.30)		1.00 (± 0.08)	0.93 (± 0.18)	0.91 (± 0.21)	0.74 (± 0.20)
<b>Mid G3</b>	0.97 (± 0.45)	0.95 (± 0.27)	0.99 (± 0.22)	0.60 (± 0.30)		0.98 (± 0.08)	0.99 (± 0.09)	0.80 (± 0.14)
<b>Wean P3</b>	0.75 (± 0.31)	0.96 (± 0.22)	0.95 (± 0.20)	0.98 (± 0.22)	0.66 (± 0.21)		0.96 (± 0.14)	0.93 (± 0.11)
<b>Late G4</b>	0.35 (± 0.35)	0.94 (± 0.30)	0.98 (± 0.19)	0.91 (± 0.24)	0.60 (± 0.26)	0.93 (± 0.15)		1.00 (± 0.13)
<b>Wean P4</b>	0.41 (± 0.68)	0.82 (± 0.45)	0.83 (± 0.44)	0.88 (± 0.38)	0.29 (± 0.50)	0.89 (± 0.30)	0.90 (± 0.32)	

<sup>1</sup>Genetic correlations estimated with pairwise bivariate animal models

<sup>2</sup>Front and rear pastern angle were objectively measured by three evaluators on pictures of sows at each time point

<sup>3</sup>Late Dev = near the end of the development period at 206 days of age, Late G1 = day 99 of first gestation, Wean P1 = weaning of parity 1, Wean P2 = weaning of parity 2, Mid G3 = day 58 of third gestation, Wean P3 = weaning of parity 3, Late G4 = day 99 of fourth gestation, Wean P4 = weaning of parity 4

Most genetic correlations between time points for foot lesion traits were below 0.8. Standard errors for foot lesion genetic correlations were approaching and, in some cases, even exceeded genetic correlation estimates. However, most genetic correlation estimates for HOE were twice their standard errors. Model convergence was not reached for some HSC and, to a lesser extent, total rear lesion score models as several time points had very low genetic variance. These traits also had the highest standard errors. More data is needed to reduce standard errors and improve model convergence before conclusions can be drawn for foot directional positioning (i.e., toed in or out) and foot

lesion traits. While body size and leg and body angle traits would certainly benefit from more data, the present results indicate that these traits likely remain the same trait genetically over time, at least from G1 to G4.

To our knowledge, this is the second study to report genetic correlations of objectively measured conformation traits evaluated on the same animals across time with the present study reporting substantially more timepoints. Stock et al. (2018) reported high genetic correlations between objectively measured knee and front pastern angles between gilt selection at 150 days of age and post first parity, in agreement with the present results. However, genetic correlations between objectively measured hock and rear pastern angles were low (Stock et al., 2018). While in the present study lower genetic correlations were observed between measurements obtained during gilt development and later time points when compared to correlations between measurements that both occurred after growth had slowed, the lowest genetic correlations in the present study were two to four times higher than those reported in Stock et al. (2018) for these traits. Only one study was identified in which genetic correlations between subjectively scored conformation traits at different time points were reported (Webb et al., 1983). Genetic correlations between subjectively scored conformation traits in boars (27 and 91 kg) that were significantly different from zero were found for forelegs turned out in both Large White and Landrace, hindlegs turned out in Large White, and hindlegs turned in for Landrace. However, while they significantly differed from zero, some of these correlations still fell below the threshold of 0.8. Genetic correlations between time points were lower and not significantly different from zero for sickle-hocked, over at the knee, and down at pasterns on the front leg (Webb et al., 1983). Conformation traits scored in

Webb et al. (1983) were on a 3-point scale and focused on defects rather than specific angle values as in the present study. Additionally, both scoring events occurred during the growth phase, which may have resulted in lower genetic correlations.

Heritability estimates and genetic correlations of body size, knee angle, hock angle, pastern angles, and rump slope presented here indicate that these traits have the same genetic basis across a substantial amount of time and could be improved via genetic selection. Previous work identified phenotypic associations between conformation traits, including BDS, BDF, HS, HF, and KA, and reproductive longevity (chapter 4). Further work is needed to validate genetic relationships between these traits, fitness, and reproductive longevity. If genetic relationships exist, these traits are excellent candidates for inclusion in a breeding program to improve sow reproductive longevity, welfare, and farm profitability.

## **5.5 Conclusions**

Conformation traits are lowly to moderately heritable indicating genetic selection is possible. Body size traits and RS were moderately heritable, while leg and foot directional position angles were lowly heritable. Most foot lesions were lowly heritable, except HOE and the total lesion score on all feet. Genetic correlations between traits measured at different time points indicate BL and RS are the same trait genetically from late dev to wean P4. Other body size traits and leg angles were the same trait over time excluding late dev and wean P4. Foot directional position (i.e., toed in or out) angles and foot lesions had high standard errors and many genetic correlations below 0.8. With the present data, these traits cannot be considered genetically the same over time. Body size and leg and body angle traits objectively measured from the side view were both

heritable and had genetic determinism that remained the same over time. Further work is needed to verify genetic correlations between these traits and reproductive longevity.

Side view traits genetically correlated to reproductive longevity would be beneficial to include in a breeding program to improve sow reproductive longevity, welfare, and farm profitability.

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## CHAPTER 6: SYNTHESIS AND CONCLUSIONS

### 6.1 Introduction

Sow reproductive longevity is a major economic and welfare concern for the swine industry as sows must produce enough marketable piglets to achieve a positive profit margin above purchase, development, and maintenance costs. However, sow reproductive longevity is a complex trait that is highly polygenic and influenced by many factors with many culling decisions being subjective management calls. Genetic improvement is difficult due to low heritability, sex-limited expression, and expression late in life. Conformation is an important factor influencing sow reproductive longevity as poor conformation and associated lameness is the second most common reason for early culling in modern swine production systems in many parts of the world. In addition to reproductive longevity, conformation may also influence reproductive performance traits, such as litter size, and other traits of economic importance. However, there are many aspects to conformation that are themselves complex traits which are influenced by many factors and difficult to phenotype. Studies assessing conformation in swine vary widely in phenotyping methods. While most have used subjective scales, the definitions of traits and number of categories in the scale differ widely between studies. The vast differences in phenotyping make drawing conclusions from the available body of research very difficult. A reliable, objective phenotyping method is needed to standardize trait measurements to make studies comparable.

Because conformation traits are influenced by many factors, their improvement must involve multi-faceted solutions and include management, nutrition, and genetic considerations. Further study is needed in all these areas as there are many factors which

may influence conformation to explore. Demonstrating reproducibility of results across production systems, physical locations, and populations will become possible if a standardized objective measurement system were identified. Therefore, the objectives of this dissertation were to evaluate reliability of an objective conformation trait measurement system and demonstrate its utility through assessment of various means of improving sow conformation. Specifically, the effect of dietary energy and lysine intake during gilt development and housing system during first gestation on sow conformation, reproductive longevity, and production were assessed. Conformational changes between 112 days of age and parity 4 weaning were reported along with phenotypic associations between conformation traits and sow reproductive longevity. Finally, heritability of conformation traits was estimated, and genetic relationships between conformation traits measured at various time points were explored.

## **6.2 Major Findings**

The objective conformation trait measurement system was reliable between multiple evaluators, especially for body size and foot directional position angles (i.e., toed in or out). Intra-class correlations were very high between multiple measurements by the same evaluator. Although not directly compared within this work, objective trait measurements provide benefits over subjective scores, including capture of the full phenotypic range of trait values and a consistent vantage point for evaluation. Analysis of the effect of developmental diet and gestation housing system treatments on objectively measured conformation traits demonstrated the ability of the objective measurement system to identify subtle conformation changes that would not have been detected with subjective scores. While changes in conformation based on dietary energy and lysine

levels during development were small, restricted energy intake was beneficial through increased lactation feed intake and litter weaning weight and reduced body condition loss in parity 1. Undesirable, albeit small, conformation changes were observed in pen compared to stall gestation housing during first gestation. Differences between developmental dietary treatments and gestation housing systems were quick to form after treatment application but were also quick to disappear once the treatment was no longer applied, indicating that conformation can change rapidly in response to environmental stimuli. Care is needed to prevent and respond to environmental challenges that may result in undesirable effects on conformation, especially at times of high removal rates such as gilt entry into the breeding herd.

All conformation traits were shown to change over time. In most cases, the greatest changes occurred during development and around weaning each parity. Despite cyclical changes that occurred along with the gestation cycle for many traits, body size and angle traits were shown to be the same trait genetically after development. However, standard errors became relatively high around fourth gestation and weaning, so additional data is needed to confirm genetic correlations involving these time points. Accurate assessment of genetic relationships of foot directional position (i.e., toed in or out) and foot lesion traits over time requires more data. Phenotypically, shorter height and greater body depth were favorable for reproductive longevity while “toed out” rear feet and knees on both ends of the phenotypic spectrum were detrimental. Heel-sole cracks and total foot lesion scores on the rear feet increased culling hazard. Objectively measured conformation traits and foot lesions are heritable and are worth continued pursuit for potential incorporation into swine breeding programs.

### 6.3 The Learning Curve

I have learned a lot in the process of completing this project, especially since I was involved in all phases of design, data collection, and analysis. Several changes were made to the project, especially in the early stages as we identified ways to improve our methods. While the improvements were overall a good thing, they did create some challenges in the analysis phase, and it of course would have been better, albeit unrealistic, to have done everything right from the start. First, we only started out with two cameras to capture side profiles and back view images but continued to add cameras as we noticed more traits that would be interesting to explore and found ways to make their capture feasible. This resulted in missing data for some traits within some cohorts and time points. For example, foot lesions were added after cohort 1 was moved into farrowing and we noticed severe lesions on the bottoms of many of their feet. Feet bottoms are not the easiest anatomical feature to access, and until we were able to procure a chute with a lift to raise the sows in the air, the best we could do was video the sows' feet while they were laying down in the farrowing facility. No data was collected from cohort 1 during development as they had just completed the developmental period when the study was initiated. We arbitrarily chose to film the right side of all sows in cohort 1, only to realize too late that it was only feasible to capture video from the left side in the development facility. Fortunately, previous research has indicated measurements between different sides of the body are repeatable, so we were able to stay consistent within a cohort and capture any variability of left vs. right side in the cohort effect within models. The timing of the development period also changed between cohorts 2 and 3 to better reflect industry practices. It was a change that needed to be made to be as industry

relevant as possible but would have been far better to have been made at the start. The most troublesome change was not imposing differential housing treatments in cohort 2 as this caused confounding between housing and cohort and did not allow me to model all the interaction effects that would otherwise have been appropriate. Housing five gilts per pen in cohort 1 did not work well from a management standpoint, but four gilts per pen should have been attempted in cohort 2 rather than waiting until cohort 3, or even better, done from the start. Gestation and farrowing facilities were remodeled during the study, making it tricky to describe facilities as required because one differential treatment imposed involved housing.

Phenotype collection is extremely important as genetic evaluations will be meaningless if phenotypes are not accurate. This project has helped me become better at thoroughly thinking through the phenotyping process. Moving forward, we have begun placing cameras directly perpendicular to both the front and hind legs to capture a more direct and closer view of the leg and using higher resolution cameras to make precise identification of each angle point of knee, hock, and pasterns easier. Intra-class correlations were higher between evaluators for measurements of the rear foot compared to the front feet; one major difference in these measurements was that the camera was positioned directly in front of the rear foot, while the front feet shared a centrally positioned camera. Side view camera position changes are expected to improve consistency of leg angle measurements between evaluators in a similar manner.

In hindsight, I wish I had been more intentional in the process of assigning undergraduate student workers images to measure. There were cases in which only one cohort was measured by a particular undergraduate student. Estimation of evaluator

effects would have benefitted from a more even distribution of evaluators across measurements. It was not feasible in real-life to make this perfect due to differences in available time and other factors between undergraduate students but could have been done better had I taken the need to estimate evaluator effects into consideration.

Finally, I was hopeful that I could improve heritability estimates and reduce standard errors by utilizing repeated measures models to increase the amount of data going into the heritability estimate. I knew this was only appropriate if traits were the same genetically at each time point and that it was not as good as having more animals, but I thought it would still be better than considering individual time points separately. However, including multiple time points necessitated including a time effect which became part of the denominator within the phenotypic variance. This resulted in larger phenotypic variances and reduced heritability. Reduced heritability would result in reduced genetic progress, and anything that can be done to reduce environmental variation and increase heritability is beneficial to a breeding program. From a practical standpoint, use of repeated measures would require additional effort and is not feasible in practice outside of a research setting. Therefore, this idea was not pursued further or included in this dissertation.

## **6.4 Future Research**

While the objective phenotyping method was shown to have merit, improvements are still necessary. In addition to improvements to side angle consistency as previously discussed, automation is essential for improvements in both efficiency and reliability. Computers can be trained to measure conformation phenotypes with better accuracy and precision than humans. The phenotyping process used in this study was very labor



intensive. The process must be simplified and made more efficient to be practical for use in industry and for further research.

Numerous management and facilities factors may influence conformation and, therefore, need further exploration. One urgent need in this area is comparisons between pen designs and floor types. The present study demonstrated detrimental effects of pens compared to stalls on conformation, but only one type of pen housing system was assessed for only one gestation period. Studies have only begun to compare the many systems used in industry today, but farms are continuing to make the transition from stall to pen housing out of necessity due to consumer demand. Guidance is lacking as to which pen housing options result in the best outcomes for conformation and reproductive longevity. Once a facility is built, these factors are extremely difficult to change, so this knowledge is needed upfront in this transition process.

The present study has only begun delving into considerations necessary to select for improved conformation. This selection occurs at both the nucleus and multiplier/commercial levels which require different considerations. Gilts are selected from the multiplier to become commercial females, where their phenotypic performance is crucial. The present study identified phenotypic associations between conformation traits and reproductive longevity. However, some of these associations were not present until after the time when gilt selection occurs. Further work is needed to determine if there is any value in performing selection on these traits at a time prior to when the trait is shown to influence reproductive longevity. Furthermore, specific trait values that are detrimental to reproductive longevity have yet to be determined. Conformation may also influence reproductive performance traits, which was not evaluated here. Estimation of

genetic parameters require large datasets for accuracy. Heritability and genetic correlation estimates presented in this work would certainly benefit from an expanded dataset. While conformation traits may have economic value themselves via consumer demand for improved animal welfare and reduced costs associated with treating lameness, their greatest contribution to economic success is likely through associations with reproductive longevity and performance. Before they can be included in an index as indicator traits, genetic correlations between conformation and economically important traits, including sow reproductive longevity and performance traits, must be assessed. Accurate estimation of these genetic parameters will require more data than was available in this study. Determining the proper timing for collection of conformation trait phenotypes for genetic evaluation is also essential. The current study found lower genetic correlations between trait values assessed during development and after breeding compared to trait values assessed at various time points after breeding. However, it would be most beneficial to phenotype individuals for conformation prior to selection rather than having to rely on phenotypes of relatives collected after breeding. Further study is needed to determine if conformation traits assessed prior to breeding are predictive of future trait values and performance. Assessment of trade-offs between earlier and later phenotyping in terms of accuracy and genetic gains may be necessary. Finally, handling intermediate optimums of some conformation traits, such as knee angle, within a selection index will be a challenge requiring consideration.