Daily feeding regimen impacts pig growth and behavior

Jessica D. Colpoys, Anna K. Johnson, Nicholas K. Gabler*

Department of Animal Science, Iowa State University, Ames, IA, 50011, USA

*Corresponding author: 201E Kildee Hall, Iowa State University, Ames, IA, 50011; E-mail:

ngabler@iastate.edu Phone: +1-515-294-7370 Fax: +1-515-294-1399

ABSTRACT

A primary swine production goal is to increase efficiency of lean tissue gains. While many swine production systems currently utilize *ad libitum* feeding, recent research suggests that altering feeding patterns may impact feed efficiency. Therefore, the objective of this study was to compare two feeding patterns and evaluate their impact on whole body tissue accretion, feeding behavior and activity in growing pigs. Forty eight individually housed gilts (55.9 ± 5.2 kg on test BW) were assigned into one of two feeding treatments: 1) **Free access to the feeder (Free Access)** or 2) twice daily access where gilts were allowed to eat *ad libitum* between 08:00-09:00 h and again from 17:00-18:00 h (2x). Pig performance was recorded weekly for 55 days and average daily gain (ADG), average daily feed intake (ADFI), and gain:feed (G:F) was calculated. Body composition was assessed in 12 gilts per treatment using dual X-ray absorptiometry (DXA) at day -3 and 55 of treatment, and tissue accretion rates were calculated. Gilt behaviors were assessed via video analysis during week 7 and included time spent eating, feeding rate, enrichment interaction, postural changes, standing, sitting, and lying behaviors. Gilts fed 2x had lower ADG and ADFI compared to **Free Access** gilts ($P \leq 0.01$); however, no treatment difference in G:F was observed ($P = 0.83$). At day 55 gilts fed 2x had a lower fat:protein compared to **Free Access** gilts ($P = 0.05$). Fat, lean, and protein accretion rates were lower in gilts fed 2x compared to those fed **Free Access** ($P = 0.01$). Gilts fed 2x ate less frequently and for a shorter duration of time, interacted with enrichment more frequently ($P \leq 0.005$), and tended to have less frequent postural changes compared to **Free Access** gilts ($P = 0.08$). No treatment differences were observed in duration of time spent standing, sitting, or lying ($P \geq 0.39$). Although feed regimen did not alter feed efficiency, these data indicate that twice daily feeding reduced gilt adiposity and growth without altering the pig's behavioral expression of

33 hunger. Therefore, twice daily feeding may be a method of increasing percent of lean tissue
34 without negatively impacting gilt welfare.

35

36 *Keywords:* activity, body composition, correlation, feed efficiency, feed frequency, lean tissue

37 accretion

1. Introduction

Multiple feed management systems are utilized in the U.S. swine industry. In grow-finish systems, *ad libitum* feeding is the most common regimen, whereas drop feeding and electronic sow feeders are commonly used for restrictive feeding of gestating sows. Differences in feed management systems are typically driven by production goals, i.e. maximal growth in grow-finish systems, reaching ideal bodyweight and condition at first mating in gilt developer units (GDU), and maintaining ideal body condition in gestating gilts and sows. While production goals vary across production stages, an overall swine industry goal is to improve feed efficiency and thus profitability. Furthermore, animal welfare is an important producer and consumer interest and the impact of feed management on pig hunger is a primary concern (1).

Feeder visit frequency varies across individual pigs, in part due to genetics (2,3), feeder design, feeding program and social status (4). Feeder visit frequency has been related to genetic selection for feed efficiency, with more feed efficient pigs visiting the feeder fewer times compared to less feed efficient pigs (2). However, studies manually altering feeding patterns have reported conflicting results related to feed efficiency and changes in body composition (5-7). Therefore, in order to provide recommendations for a feeding system that is most beneficial for production goals, more conclusive information is necessary.

Surprisingly, few studies have related pig behavior to nutrient utilization and growth. Therefore, understanding how feeding regimen and efficiency of lean growth impacts pig behavior is important, as feeding behavior and activity can be indicators of hunger and satiety (8,9). Furthermore, behavior can partially explain differences in energy expenditure (10). Schneider and colleagues (7) and Brouns and colleagues (11) reported that pigs fed fewer times

spent a shorter duration of time eating. However, these authors reported conflicting pig activity results.

Therefore, the objective of this study was to compare two feeding patterns and to evaluate their impact on gilt nutrient utilization and whole body tissue accretion, feeding behavior and activity. Our second objective was to relate gilt feeding behavior and activity to nutrient utilization and whole body tissue accretion. Our hypothesis was that gilts fed **free access** would utilize nutrients less efficiently for lean tissue gains, spend more time eating and be more active compared to gilts fed less frequently. We also hypothesized that gilt behavior would correlate with nutrient utilization and whole body tissue accretion. This study utilized 56 to 114 kg BW female pigs (gilts) as a model for evaluating two feeding patterns. These results can therefore be applied to gilts within grow-finish systems and GDUs.

2. Materials and methods

All experimental procedures were approved by the Iowa State University Animal Care and Use Committee (IACUC# 8-14-7851-S). This work was conducted at Iowa State University from October to December, 2014.

2.1 Animals and housing

Forty-eight crossbred female pigs (gilts; 55.9 ± 5.2 kg on test BW) were blocked by body weight into two feeding treatments: 1) **Free access to feeders (Free Access;** n = 24) or 2) twice daily feed access (2x; n = 24). The 2x treatment allowed gilts to eat *ad libitum* between 08:00-09:00 h and again from 17:00-18:00 h. The 2x feeding treatment was chosen as an alternative regimen to **Free Access** feeding based on the results of Young and colleagues (2) who observed

that more feed efficient pigs had fewer feeder visits at the two peak meal times that occurred between 8:00-10:00 and 14:00-18:00 h. All gilts received either feeding treatments for 55 days **and this will be referred to as 7 weeks.** Both treatments were fed the same corn-soybean mash diet in three phases that met or exceeded NRC (12) requirements for this size of pig. The phase 1 diet was formulated to contain 13.88 MJ/kg metabolizable energy (ME) and 0.96% standardized ileal digestible (SID) lysine. The phase 2 diet was formulated to contain 13.89 MJ/kg ME and 0.87% SID lysine, and the phase 3 diet was formulated to contain 13.92 MJ/kg ME and 0.78% SID lysine. **Diet phase changes were made when pigs individually reached specific BW; therefore, phase 1 diet was fed initially through 70 ± 10 kg BW, phase 2 diet was fed from 70 through 90 ± 10 kg BW, and the phase 3 diet was fed from 90 ± 10 kg BW through the end of the study.**

All gilts were housed in individual pens measuring 2.21 m long x 0.61 m wide within nose to nose contact with each other. All pens were located within one climate controlled room, set to the thermoneutral requirements for this size of pig. An electronic recording device (HOBO Pro v2, temp / RH, U23-001, Onset Computer Corporation, Bourne, MA, USA) was located within the room to record ambient temperature ($^{\circ}\text{C}$) and relative humidity (%). The mean ($\pm$ S.D.) ambient temperature was $19.9 (\pm 1.2) ^{\circ}\text{C}$ and relative humidity was $60.8 (\pm 5.7) \%$. **Lights were on a 12:12 light dark cycle with light hours from 7:00-19:00 h.** Each pen was located on slatted concrete flooring and contained a polypropylene rope tied to an overhead bar for environmental enrichment, a water nipple, and a single-space feeder with a lid. To achieve the 2x feeding treatment, feeders were latched to prevent gilts from accessing feed during non-meal times (Fig. 2.1). Gilts were acclimated to this housing for three days prior to the commencement of feeding treatments. Within the same room, gilts were stalled next to other gilts of the same

treatment and a solid visual barrier was located between pens separating **Free Access** and 2x treatment to avoid synchronized feeding (13).

2.2 Performance

Gilt body weight and feeder weights were measured weekly over 7 consecutive weeks. These data were used to calculate average daily gain (ADG), average daily feed intake (ADFI), and feed efficiency (gain:feed, G:F). Feeding rate was determined during week 7 for each treatment by measuring feed disappearance from feeders at 8:00, 9:00, 17:00, and 18:00 h. Feeding rate was calculated by dividing feed intake by the duration of time spent eating (see section 2.4).

2.3 Whole body composition and tissue accretion

Longitudinal whole body composition was assessed in 12 gilts per treatment using a Hologic Discovery A Dual X-ray Absorptiometry (DXA) machine (Bedford, MA, USA) before (day -3; initial scan) and after (day 55; final scan) the 7 week performance period. To ensure that gilts remained stationary during DXA scanning, gilts were anesthetized using xylazine (4.4 mg per kg; Anased, Lloyd Laboratories, Shenandoah, IA, USA), ketamine HCl (2.2 mg per kg; Ketaset, Wyeth, Madison, NJ, USA), and tiletamine HCl and zolazepam HCl in combination (4.4 mg per kg; Telazol, Wyeth, Madison, NJ, USA) prior to the initial DXA scan. Immediately prior to the final DXA scan, gilts were humanely euthanized by captive-bolt and scanned. The DXA output provided information on whole body bone, fat, and lean tissue mass. Scan data was corrected using internally built calibration curves **for pigs** using the following regressions: Live weight, $y = 1.0822x - 1.826$, $R^2 = 0.997$; Fat, $y = 0.9515x - 1.06$, $R^2 = 0.9308$; Bone mineral ash, $y = 2.1473x - 0.1411$, $R^2 = 0.9219$; Lean, $y = 1.0668x - 0.1411$, $R^2 = 0.9909$; Protein, $y = 0.2206x - 0.6611$,

$R^2=0.9758$. Where x = DXA results and y = chemical proximate on an empty whole body (i.e. no luminal, urine or gall bladder contents). **These calibration curves were built as described by Suster et al. (25).** Tissue accretion was calculated by determining the net change between final and initial body compositions, divided by the days between scans.

2.4 Behavior

To assess gilt behavior, eight color cameras (Panasonic, Model WV-CP-484, Matsushita Co. LTD., Kadoma, Japan) were positioned above the pens. The cameras were fed into a multiplexer using Noldus Portable Lab (Noldus Information Technology, Wageningen, The Netherlands) and time-lapse video was collected onto a computer using HandyAVI (version 4.3, Anderson's AZcendant Software, Tempe, AZ, USA) at 10 frames/s. Video was continuously analyzed during week 7 for 36 hours starting at 7:00 h and ending at 19:00 h the following day. Video observations were collected using the Observer software (The Observer XT version 10.5, Noldus Information Technology, Wageningen, The Netherlands) by four trained observers who had intra- and inter-observer reliabilities of $\geq 80\%$. Eating, postural changes, standing, sitting, and lying behaviors were collected for all 48 gilts and enrichment interaction was collected on 23 gilts (2x $n = 12$ and **Free Access** $n = 11$; Table 1).

2.5 Data analysis

All data were evaluated for normality using the Shapiro-Wilk test and Q-Q plots using SAS (version 9.4, SAS Inst., Cary, NC, USA). Performance, body composition, and tissue accretion data were normally distributed; therefore, were analyzed using the Mixed procedure of SAS. The model included the fixed effects of treatment and pig as the experimental unit. To account for

initial variation in BW the covariate of initial BW was used for all performance, body composition, and tissue accretion measures except for initial BW itself. Initial body composition was used as a covariate for the respective parameter. Weekly performance was analyzed using a repeated measures model with the fixed effects of treatment, week, and their interaction. The covariate of weekly BW was used for all weekly performance measures except for weekly BW itself. Correlations among overall performance and whole body tissue accretion variables were performed using Pearson correlations. Behavior data were not normally distributed; therefore, were analyzed using the Glimmix procedure of SAS. Feeding rate and duration data were analyzed with a gamma distribution and frequency data were analyzed with a Poisson distribution. The model included the fixed effects of treatment, covariate of week 7 BW, and pig as the experimental unit. To directly compare feeding rate during meal times, the model also included the fixed effects of meal time and the treatment by meal time interaction. Correlations of behaviors with overall performance and whole body tissue accretion variables were performed using Spearman rank correlations. The significance level was fixed at $P \leq 0.05$ and tendency at $0.05 < P \leq 0.10$ for all data analyses.

3. Results

3.1 Performance

Weekly gilt performance differences are reported in Figure 1. A treatment, week, and treatment x week interaction was observed for BW ($P \leq 0.05$), ADFI ($P \leq 0.03$), ADG ($P < 0.0001$), and G:F ($P \leq 0.0002$). **Gilts fed 2x had a lower BW weeks 3 through 7 ($P \leq 0.04$) and lower ADFI weeks 1, 2 and 4 compared to Free Access gilts ($P \leq 0.04$). These gilts also had lower ADG weeks 2 and 4 ($P \leq 0.003$) and lower G:F weeks 2 and 7 compared to Free**

Access gilts ($P \leq 0.02$). However, 2x gilts had greater ADG week 6 compared to Free Access gilts ($P = 0.02$).

Overall gilt performance differences for the 55 day test period are reported in Table 2. Gilts fed 2x had a 0.23 kg/day lower ADFI compared to ad lib, which translated into in uptake of 3.1 MJ/day less energy by the 2x gilts ($P = 0.005$). These gilts also had a 0.07 kg/day lower ADG which resulted in a 4.25 kg lower final BW compared to **Free Access** gilts ($P = 0.01$). No overall G:F differences were observed between treatments ($P = 0.83$). As expected, ADFI and ADG were highly correlated ($P < 0.0001$) and ADG tended to be weakly correlated to G:F ($P = 0.07$; Supplemental Table 1).

3.2 Whole body composition and tissue accretion

As expected, initial whole body composition (i.e. fat, lean, protein, and bone mineral content) did not differ between treatments ($P \geq 0.54$; *data not presented*). However, at the end of the study gilts fed 2x had 2.51 kg less fat, 3.45 kg less lean, and 0.73 kg less protein on a whole body basis compared to gilts treatment **Free Access** ($P \leq 0.02$). This translated into gilts fed 2x having a lower fat:protein compared to **Free Access** gilts ($P = 0.05$). The whole body percent of bone mineral content (BMC) and bone mineral density (BMD; $P \geq 0.21$) did not differ. Fat, lean, and protein tissue accretion rates were lower in gilts fed 2x compared to those fed **Free Access** ($P = 0.01$); however, no treatment differences were observed in BMC accretion ($P = 0.28$; Table 3). All measures of whole body tissue accretion showed a positive, moderate to strong correlation with other measures of whole body tissue accretion ($P \leq 0.04$), ADG ($P \leq 0.01$), and ADFI ($P \leq 0.01$). Lean and protein accretion showed a positive, moderate correlation with G:F ($P \leq 0.05$; Supplemental Table 1).

3.3 Behavior

Gilt behavior differences are reported in Table 4. Gilts fed 2x ate less frequently and for a shorter duration across the 36 hour behavior observation compared to **Free Access** gilts ($P < 0.0001$). Looking at the 36 hour behavior window, overall feeding rate did not differ between feeding regimen ($P = 0.15$); however, when specifically comparing feeding rate at the two meal times 2x gilts were observed eating 6.52 g/min faster than **Free Access** gilts ($P = 0.005$). Regardless of treatment, gilts ate 8.38 g/min slower during the 8:00-9:00 h meal time than during the 17:00-18:00 h meal time ($P = 0.0002$). No feeding rate treatment by meal time interaction was observed ($P = 0.20$; Fig. 2). Gilts fed 2x interacted with the enrichment more frequently compared to **Free Access** gilts ($P = 0.0002$); however, no treatment difference in duration of time spent interacting with enrichment was observed ($P = 0.38$). Gilts fed 2x tended to display less frequent postural changes compared to **Free Access** gilts ($P = 0.08$). No treatment differences were observed in duration of time spent standing, sitting, or lying ($P \geq 0.39$; Table 4).

To further understand how behaviors relate to overall performance and whole body tissue accretion a correlation analysis was conducted. Duration of time spent eating showed a positive, moderate correlation with ADG, ADFI, fat tissue accretion ($P \leq 0.04$), and tended to be positively correlated with lean tissue accretion ($P = 0.09$). Duration of time spent interacting with enrichment showed a negative, moderate correlation with ADG ($P = 0.006$) and tended to be negatively correlated with ADFI ($P = 0.08$). Postural changes tended to be positively correlated with BMC accretion ($P = 0.07$). Duration of time spent standing was weakly and negatively correlated with ADG and ADFI ($P \leq 0.02$). Duration of time spent lying showed a positive, weak

correlation with ADG ($P = 0.02$). No other significant behavioral correlations with overall performance and whole body tissue accretion were observed (Table 5).

4. Discussion

Young and colleagues (2) observed that more feed efficient pigs fed *ad libitum* had fewer feeder visits at two peak meal times occurring between 8:00-10:00 and 14:00-18:00 h; therefore, 2x feeding was chosen as an alternative regimen to compare to **Free Access** feeding. This study utilized 56 to 114 kg BW gilts as a model for evaluating two feeding regimen. This size of gilt is commonly utilized in grow-finish systems and GDUs; therefore, these results can be applied to gilts within these systems. **Further, these data could be extended to boar studs where boars are individually housed.** However, it is important to note that our gilts were individually penned whereas gilts within grow-finish systems and GDUs are commonly housed in group pens. **Therefore, future studies investigating implementation of twice daily feeding within group housing systems is warranted, but welfare needs to be studied as it relates to group housing.**

Across the seven week trial, the benefit of lower ADFI in 2x compared to **Free Access** gilts was offset by lower ADG and therefore resulted in no G:F treatment differences. Average daily feed intake was correlated with duration of time spent eating; therefore, the reduced ADFI is likely due to a lower duration of time spent eating and may also relate to a lower frequency of eating in 2x compared to **Free Access** gilts. This may be partially explained by the 60 min time allotted for each 2x meal. Newman and colleagues (5) observed a tendency for boars fed two 60 min meals to eat less than ad lib; however, in a separate experiment, boars fed two 90 min meals ate a similar amount as ad lib. In contrast to the current study, Newman and colleagues (5) did not observe a difference in ADG between boars fed two 60 min meals and ad lib, and therefore

observed improved feed efficiency in boars fed two 60 min meals. **This difference may be partially explained by differences in pig sex between the studies (i.e. gilts vs. boars).** Interestingly, at week 2 we observed a 40% lower G:F in 2x compared to **Free Access** gilts, largely driven by a 38% lower ADG. This suggests an acclimation period for pigs fed the 2x feeding regimen; therefore, differences in study length may partially explain discrepancies between earlier studies (5-7).

Based on pigs fed two versus twelve meals daily, gilts fed less frequent meals were shown to have increased ADG and G:F (6). Therefore, based on the assumption that gilts fed *ad libitum* would eat more frequently than gilts fed twice daily, we hypothesized that gilts fed *ad libitum* would utilize nutrients less efficiently for lean tissue gains than gilts fed 2x. The reduced fat, lean, and protein accretion rates observed in 2x compared to **Free Access** gilts largely reflects ADG differences, and thus we reject this hypothesis. However, when evaluating final whole body composition, 2x gilts had a lower fat to protein ratio. These differences may be partially explained by ADFI, as ADFI increases fat accretion and also protein accretion which requires 16% less energy than fat (14). Dietary energy is therefore first partitioned towards maintenance needs, then towards lean accretion, and excess energy is partitioned towards fat accretion (15).

Newman and colleagues (5) evaluated insulin concentrations of pigs fed *ad libitum* versus two meals, where gilts were allowed *ad libitum* access to feed during the two meal times. These authors reported that twice daily feedings increased post-prandial insulin concentrations, whereas pigs fed *ad libitum* maintained relatively constant plasma insulin concentrations. As insulin plays an important role in stimulating protein synthesis (16), feeding regimen may impact protein metabolism. Le Naou and colleagues (6) also evaluated insulin as well as urea, and α -amino

nitrogen in pigs fed two versus twelve meals daily. These authors reported twice daily fed pigs had a greater rise and fall of plasma insulin concentrations compared to 12 meals; therefore, pigs fed 12 meals may correspond to ad libitum pigs in work by Newman and colleagues (5) and the current study. Le Naou and colleagues (6) also reported that pigs fed meals twice daily had lower plasma concentrations of urea and α -amino nitrogen compared to pigs fed 12 meals daily. These data suggest that pigs eating less-frequent meals may have decreased protein catabolism. This notion is further supported by work in young pigs which showed that administration of the amino acid leucine every four hours enhanced skeletal muscle protein synthesis compared to continuous orogastric feeding (17). This suggests that meal frequency is important to support lean tissue growth efficiency and that dietary leucine pulsation is an important regulator of protein translation initiation. However, as this did not translate to increased protein accretion in the 2x gilts of the current study, leucine pulsation may need to occur more than twice daily to enhance protein synthesis.

Access to feed and boredom of pigs can lead to changes in behavior, welfare and productivity (18,19). Therefore, one of our objectives was to evaluate how feeding frequency alters gilt behavior. Schneider and colleagues (7) reported that pigs fed two meals daily spent less time eating than those fed six meals daily. Therefore, we hypothesize that the **Free Access** gilts in the current study ate more frequent meals than 2x gilts. Assuming that gilts are motivated by hunger or reduced satiation to interrupt a behavioral state such as lying (9,20), the tendency of **Free Access** gilts to have more postural changes than 2x gilts further supports the hypothesis that **Free Access** gilts ate more frequent meals. Due to the methodology of behavioral collection, feeding frequency represents the number of times the pig's mouth and nose entered the feeder rather than the number of meals the pig ate. Therefore, the pig's mouth and nose often exited the

feeder in order to drink, root, and chew environmental enrichment rather than signify the end of a meal. However, the duration of time spent eating as well as ADFI clearly indicate feeding differences due to feeding regimen.

Feeding rate is reported to reflect feeding motivation in pigs; with faster rates suggesting increased feeding motivation (21). Therefore, when directly comparing feeding rate at the meal times the increased feeding rate of the 2x gilts suggests that they are more motivated to eat than the **Free Access** gilts. This is likely a result of the limited feeding time available to the 2x gilts since no difference in overall 36 hour feeding rate was observed. This may suggest that overall feeding motivation did not differ between treatments across the 36 hour behavioral observation period.

Increased standing and reduced lying time has been shown to reflect pig behavioral expression of hunger (8,9,22). In the current study, duration of time spent standing was negatively correlated with ADFI; however, whether this is related to hunger and/or reduced energy intake is unclear. No treatment differences were observed in the duration of time spent standing, sitting, or lying, suggesting no treatment differences in hunger. These results are in contrast to other studies that observed feeding regimen differences in the duration of time spent standing and lying (7,11). However, these studies evaluated behavior of pigs housed in groups rather than individually. Therefore, future studies investigating implementation of twice daily feeding on pig hunger within group housing systems is warranted. Increased NEFA concentrations have been related to increased hunger in pigs (9). Newman and colleagues (5) did not observe differences in NEFA concentrations in pigs fed twice daily versus *ad libitum*. Therefore, this supports the behavioral observation of the current study that gilts fed 2x versus **Free Access** did not differ in hunger.

Gilts fed 2x interacted with the enrichment more frequently compared to ad lib. These results agree with Zwicker and colleagues (18) who reported that pigs restrictively fed interacted with straw environmental enrichment more frequently than pigs fed ad lib. In humans, it has been reported that prolonged mastication reduces self-reported hunger (23). Additionally, cognitive enrichment in pigs has been shown to reduce stress associated with feeding (24). Therefore, interacting with enrichment may serve as a mechanism for coping with hunger or stress associated with restricted access to feed. In the current study it was observed that the duration of time spent interacting with enrichment tended to negatively correlate with ADFI. This suggests that enrichment interaction may be a redirected foraging behavior or may reduce hunger. Enrichment interaction also appears to be energetically demanding as duration of time spent interacting with enrichment is negatively correlated with ADG; however, it did not significantly alter G:F. Future studies investigating the use of environmental enrichment as a coping mechanism for restrictively fed pigs is warranted as it may positively impact pig welfare.

4.4 Conclusion

Feed efficiency is impacted by a number of factors internal and external to the pig (15); therefore, modifying feeding regimen may not be a reliable method of improving feed efficiency. Due to observed reduced growth of gilts fed 2x, **Free Access** feeding may be a better regimen for grow-finish systems seeking to maximize throughput and GDUs seeking to maximize growth rate. However, twice daily feeding reduced the fat to protein ratio. As this is a U.S. grow-finish swine production goal, twice daily feeding may have implications for future developments in precision livestock farming. Reduced percent of fat is often observed when restrictive feeding pigs (15), but restrictive feeding may have negative consequences on gilt welfare as they may not

reach satiety (22). The current study did not observe differences in overall behavioral expression of hunger; therefore, twice daily feeding may be a method of increasing percent of lean tissue without negatively impacting gilt welfare.

Acknowledgements

This project was supported by the Agriculture and Food Research Initiative Competitive Grant no. 2011-68004-30336 from the USDA National Institute of Food and Agriculture. We would like to thank Stephanie Lindblom, Rebecca Parsons, Megan Righi, and Wes Schweer for assistance in data collection and animal care, Amber Haritos, Paige Mercer, and Kirsten Springman for assistance with video analysis, Ken Colpoys for designing and mounting latches for the 2x feeders, and Caitlyn Abell for statistical consulting.

References

- [1] D'Eath RB, Tolkamp BJ, Kyriazakis I, Lawrence AB. 'freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. *Animal Behaviour* 2009;77:275-288.
- [2] Young JM, Cai W, Dekkers JCM. Effect of selection for residual feed intake on feeding behavior and daily feed intake patterns in yorkshire swine. *Journal of Animal Science* 2011;89:639-647.
- [3] Huisman AE, van Arendonk JAM. Genetic parameters for daily feed intake patterns of growing dutch landrace gilts. *Livestock Production Science* 2004;87:221-228.
- [4] Nielsen BL, Lawrence AB, Whittemore CT. Effect of group-size on feeding-behavior, social-behavior, and performance of growing pigs using single-space feeders. *Livestock Production Science* 1995;44:73-85.
- [5] Newman RE, Downing JA, Thomson PC, Collins CL, Henman DJ, Wilkinson SJ. Insulin secretion, body composition and pig performance are altered by feeding pattern. *Animal Production Science* 2014;54:319-328.
- [6] Le Naou T, Le Floc'h N, Louveau I, van Milgen J, Gondret F. Meal frequency changes the basal and time-course profiles of plasma nutrient concentrations and affects feed efficiency in young growing pigs. *Journal of Animal Science* 2014;92:2008-2016.
- [7] Schneider JD, Tokach MD, Goodband RD, Nelssen JL, Dritz SS, DeRouchey JM, Sulabo RC. Effects of restricted feed intake on finishing pigs weighing between 68 and 114 kilograms fed twice or 6 times daily. *Journal of Animal Science* 2011;89:3326-3333.
- [8] Beattie VE, O'Connell NE. Relationship between rooting behaviour and foraging in growing pigs. *Animal Welfare* 2002;11:295-303.

- 369 [9] Toscano MJ, Lay DC, Craig BA, Pajor EA. Assessing the adaptation of swine to fifty-
370 seven hours of feed deprivation in terms of behavioral and physiological responses.
371 Journal of Animal Science 2007;85:441-451.
- 372 [10] Schrama JW, Bakker GCM. Changes in energy metabolism in relation to physical
373 activity due to fermentable carbohydrates in group-housed growing pigs. Journal of
374 Animal Science 1999;77:3274-3280.
- 375 [11] Brouns F, Edwards SA, English PR. Effect of dietary fiber and feeding system on activity
376 and oral behavior of group-housed gilts. Applied Animal Behaviour Science
377 1994;39:215-223.
- 378 [12] NRC. Nutrient requirements of swine. National Academies Press, 2012.
- 379 [13] Hsia LC, Wood-Gush DGM. The temporal patterns of food intake and allelomimetic
380 feeding by pigs of different ages. 1984;11:271-282.
- 381 [14] Patience JF. The influence of dietary energy on feed efficiency in grow-finish swine. In:
382 Feed efficiency in swine, Patience JF (Ed.), Wageningen Academic Press, 2012, pp 101-
383 129.
- 384 [15] Patience JF, Rossoni-Serao MC, Gutierrez NA. A review of feed efficiency in swine:
385 Biology and application. Journal of Animal Science and Biotechnology 2015;6:33.
- 386 [16] McNurlan MA, Anthony TG. Protein synthesis and degradation. In: Biochemical,
387 physiological, and molecular aspects of human nutrition, Stipanuk MH (Ed.), Elsevier,
388 2006, pp 319-357.
- 389 [17] Boutry C, El-Kadi SW, Suryawan A, Wheatley SM, Orellana RA, Kimball SR, Nguyen
390 HV, Davis TA. Leucine pulses enhance skeletal muscle protein synthesis during

- continuous feeding in neonatal pigs. American Journal of Physiology-Endocrinology and Metabolism 2013;305:E620-E631.
- [18] Zwicker B, Gygax L, Wechsler B, Weber R. Short- and long-term effects of eight enrichment materials on the behaviour of finishing pigs fed ad libitum or restrictively. Applied Animal Behaviour Science 2013;144:31-38.
- [19] Hill JD, McGlone JJ, Fullwood SD, Miller MF. Environmental enrichment influences on pig behavior, performance and meat quality. Applied Animal Behaviour Science 1998;57:51-68.
- [20] Tolkamp BJ, Allcroft DJ, Austin EJ, Nielsen BL, Kyriazakis I. Satiety splits feeding behaviour into bouts. Journal of Theoretical Biology 1998;194:235-250.
- [21] Nielsen BL. On the interpretation of feeding behaviour measures and the use of feeding rate as an indicator of social constraint. Applied Animal Behaviour Science 1999;63:79-91.
- [22] Bolhuis JE, van den Brand H, Bartels AC, Oostindjer M, van den Borne JJGC, Kemp B, Gerrits WJJ. Effects of fermentable starch on behaviour of growing pigs in barren or enriched housing. Applied Animal Behaviour Science 2010;123:77-86.
- [23] Miquel-Kergoat S, Azais-Braesco V, Burton-Freeman B, Hetherington MM. Effects of chewing on appetite, food intake and gut hormones: A systematic review and meta-analysis. Physiology & Behavior 2015;151:88-96.
- [24] Zebunke M, Puppe B, Langbein J. Effects of cognitive enrichment on behavioural and physiological reactions of pigs. Physiology & Behavior 2013;118:70-79.
- [25] **Suster D, Leury BJ, Ostrowska E, Butler KL, Kerton DJ, Wark JD, Dunshea, FR. Accuracy of dual energy X-ray absorptiometry (DXA), weight and P2 back fat to predict**

414 whole body and carcass composition in pigs within and across experiments. **Livestock**
415 **Production Sciences 2003; 84:231-242**

416

417

418 **Figure legends**

419 **Figure 1.**

420 Weekly body weight (BW, a), average daily feed intake (ADFI, b), average daily gain (ADG, c),
421 and gain:feed ratio (G:F, d) for gilts undergoing twice daily (2x; n=24) or **free access to feeders**
422 (**Free Access**; n=24) feeding treatments. ‘*’ indicates significance at $P \leq 0.05$ and ‘#’ indicates
423 tendency at $0.05 < P \leq 0.10$.

424

425 **Figure 2.**

426 Feeding rates of gilts undergoing twice daily (2x; n=12) or **free access to feeders (Free Access;**
427 **n=12)** feeding treatments. Different superscripts indicate significance at $P \leq 0.05$. ‘#’ indicates
428 tendency at $P = 0.07$.

429 **Table 1.** Ethogram of behaviors recorded during week 7 of the study. Frequency (n) and/or
 430 duration (min) of behaviors were collected.

Measure	Description
Eat (n, min)	The feeder lid is up with the pig's mouth and nose located within the feeder.
Enrichment interaction (n, min)	Oral and/or nasal contact with the environmental enrichment rope.
Postural changes (n)	Sum of the frequency of stand, sit, and lie postures.
Stand (min)	All four hooves are on the pen floor with limbs extended or the pig is walking with limbs in both extension and flexion and moving throughout the pen.
Sit (min)	The front limbs are extended and bearing weight and the rear limbs and body are in contact with the pen floor.
Lie (min)	The pig's body and limbs are in contact with the pen floor.

431

Table 2. Overall performance differences collected throughout the 7 week study period (least square means $\pm$ SE) in gilts undergoing twice daily (2x; n=24) or *ad libitum* (n=24) feeding treatments.

Measure	Treatment						P-value
	2x			Free Access			
Initial BW, kg	55.85	±	1.07	56.04	±	1.07	0.90
Final BW, kg	109.40	±	1.14	113.65	±	1.14	0.01
ADFI, kg/d	2.81	±	0.05	3.04	±	0.05	0.005
Average daily ME intake, MJ/day	39.09	±	0.74	42.19	±	0.74	0.005
ADG, kg/d	0.94	±	0.02	1.01	±	0.02	0.01
G:F, kg/kg	0.33	±	0.004	0.33	±	0.004	0.83

Table 3. Final whole body composition and overall tissue accretion rates (least square means $\pm$ SE) of gilts undergoing twice daily (2x; n=12) or *ad libitum* (n=12) feeding treatments.

Measure	Treatment						P-value
	2x			Free Access			
Final whole body composition							
Fat, %	21.92	±	0.34	23.08	±	0.34	0.03
Fat, kg	25.10	±	0.60	27.61	±	0.60	0.008
Lean, kg	86.04	±	0.98	89.49	±	0.98	0.02
Protein, kg	15.87	±	0.20	16.60	±	0.20	0.02
Fat:Protein	1.58	±	0.03	1.67	±	0.03	0.05
BMC ¹ , g	3209.11	±	92.78	3363.24	±	92.78	0.25
BMD ² , g/cm ²	1.07	±	0.02	1.11	±	0.02	0.21
Whole body tissue accretion							
Fat, g/d	296.90	±	11.02	338.90	±	11.02	0.01
Lean, g/d	672.60	±	16.66	736.60	±	16.66	0.01
Protein, g/d	135.90	±	3.42	149.10	±	3.42	0.01
BMC, g/d	35.12	±	1.62	37.64	±	1.62	0.28

¹BMC = Bone mineral content

²Bone mineral density

445 **Table 4.** Behavior (least square means $\pm$ SE) of gilts undergoing twice daily (2x; n=24) or *ad*
446 *libitum* (n=24) feeding treatments. Video was continuously analyzed during week 7 for 36 hours
447 starting at 7:00 h and ending at 19:00 h the following day.

Measure	Treatment						P-value
	2x			Free Access			
Eat, n	67.97	±	1.72	127.04	±	2.39	<0.0001
Eat, min	168.93	±	9.74	283.08	±	16.33	<0.0001
Overall feeding rate, g/min	36.36	±	2.39	31.59	±	2.07	0.15
Enrichment interaction, n ¹	53.25	±	2.24	39.44	±	1.95	0.0002
Enrichment interaction, min ¹	50.30	±	15.59	76.51	±	24.85	0.38
Postural changes, n	139.22	±	2.48	145.86	±	2.54	0.08
Stand, min	411.47	±	25.73	380.52	±	23.80	0.39
Sit, min	116.85	±	19.71	129.77	±	21.89	0.67
Lie, min	1606.65	±	24.73	1618.48	±	24.92	0.74

448 ¹Enrichment interaction was collected on n=12 2x and n=11 **Free Access** gilts

449 **Table 5.** Spearman rank correlations of behaviors with overall performance and overall whole body tissue accretion.

	Behavior								
	Eat, n	Eat, min	Overall feeding rate, g/min	Enrichment interaction, n ³	Enrichment interaction, min ³	Postural changes, n	Stand, min	Sit, min	Lie, min
Overall Performance¹									
ADFI, kg/d	0.17	0.42**	0.10	-0.01	-0.38 [#]	-0.02	-0.35**	0.08	0.23
ADG, kg/d	0.13	0.40**	0.12	-0.20	-0.55**	-0.03	-0.34*	-0.005	0.34*
G:F, kg/kg	-0.06	0.01	0.07	-0.17	-0.28	0.07	-0.10	0.05	0.17
Whole body tissue accretion²									
Fat, g/d	0.06	0.42*	-0.21	-0.32	-0.47	0.15	-0.26	-0.08	0.15
Lean, g/d	0.22	0.35 [#]	-0.20	-0.31	-0.40	0.11	-0.10	0.08	-0.12
Protein, g/d	0.16	0.32	-0.20	-0.27	-0.41	0.10	-0.10	0.07	-0.11
BMC, g/d	-0.09	0.13	0.05	-0.34	-0.51	0.38 [#]	-0.21	0.00	0.13

450 ¹n=24 gilts per treatment

451 ²n=12 gilts per treatment

452 ³Overall performance: n=12 2x and n=11 ad lib; Whole body tissue accretion: n=5 2x and n=6 **Free Access**

453 **Indicates significance at $P \leq 0.01$, * Indicates significance at $P \leq 0.05$, #Indicates tendency at $P \leq 0.1$