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M.S. or Ph.D.: Ph.D.  Expected Date of Graduation (month/year): May 2020

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**STATIC AND DYNAMIC SPACE USAGE OF LATE GESTATION SOWS**

Suzanne M. Leonard, Hongwei Xin, Brett C. Ramirez, John P. Stinn, Somak Dutta, Kai Liu

**HIGHLIGHTS**
- A calibration procedure was conducted using a Kinect V2® to convert pixel to physical measurements
- 61 sows were observed and their static and dynamic space usage measured from depth images
- Minimum gestation stall dimensions were proposed based on sow space usage

**ABSTRACT.**

The amount of space provided to individually housed gestating sows has both financial and welfare implications. Many U.S. swine producers use gestation stall dimensions based on recommendations published in the 1980s (L × W × H: 213 × 61 × 100 cm). The physical characteristics of sows have changed since then, but limited empirical data are available concerning the space allocation needed to accommodate modern gestating sows. This study used a time-of-flight depth sensor to quantify static and dynamic space usage of 61 modern sows in late gestation. A calibration equation was developed to accurately convert image pixels to physical dimensions. Statistical models were developed to relate length, width, and height of sow space usage to body weight. Results showed that to accommodate free choice space usage of small to average (228 kg) sows, minimum gestation stall dimensions need to be 196 × 115 × 93 cm (L × W × H). To accommodate average to 95th percentile (267 kg) sows, minimum stall dimensions need to be 204 × 112 × 95 cm. The 95th percentile sow space usage had a 4% decrease in length, 84% increase in width, and 5% decrease in height compared to typical gestation stall dimensions. These results help to inform future gestating sow housing designs. Further work is needed to understand how restrictions on sow space usage may impact sow welfare, as well as the space needed to perform behaviors such as feeding and turning around.

**Keywords.** Animal welfare, computer vision, gestation stall, Kinect V2®, space allowance

**INTRODUCTION**

Space allocation in gestating sow housing is an important economic and animal welfare issue for commercial swine producers. Excess space per animal increases barn construction, equipment, and maintenance costs; conversely, inadequate space provision could lead to reduced sow welfare,
development of sores, and reduced productivity (Curtis et al., 1988; Barnett et al., 2011). Many commercial U.S. swine producers utilizing gestation stalls implement a standard 213 × 61 × 100 cm (L × W × H) design (Midwest Plan Service, 1983). However, this recommendation has become outdated as there have been many advancements and changes in swine performance and physical size. There is also a trend of increasing litter size for modern commercial sows, suggesting that sow body capacity has increased (Rutherford et al., 2013). In 2011, Danish Landrace × Large White sows were determined to have increased on average 7 cm in body length and 24 kg in weight compared to measurements from a similar sow breed taken in 1994 (Moustsen et al., 2011). These results illustrate the trend of increasing sow physical dimensions and the need of reevaluating the size of gestating sows for efficient housing designs.

Traditionally, two types of quantitative methods have been used to assess the physical size of pigs to evaluate housing designs. Contact methods, such as direct measurement (i.e., with measuring tape, ruler, or calipers), depend on cooperative animals to achieve low error (Baxter and Schwaller, 1983; Curtis et al., 1989; McGlone et al., 2004; Moustsen et al., 2011). This method limits the number of pigs that can be observed, as it can be stressful for the animal and labor intensive for the researchers. Moreover, contact methods can only evaluate the static space the pigs occupy when in one postural position and are unable to directly capture the dynamic space usage when transitioning between postures. Accurate dynamic space information is critical for facility design, as sows will need to perform these transitions when housed in stalls (Baxter et al., 2011). Static measurements can be extrapolated to dynamic space requirements with empirical relationships; however, these relationships were developed based on the outdated sow body types of over 30 years ago (Baxter and Schwaller, 1983; Petherick, 1983).

Non-contact methods, such as analysis of 2D digital images, have been developed to evaluate both static and dynamic space utilization of sows. This approach provides the ability to cumulatively evaluate the space occupied by a sow as she performs dynamic postural transitions (Baxter and Schwaller, 1983; Mumm et al., 2019). However, digital imaging methods can result in errors when converting from pixel
measurements to physical dimensions. The conversion factor between pixels and physical units differs based on distance between the sow and the camera. This distance fluctuates as the sow transitions between postures and is difficult to assess in digital images. One solution to this challenge associated with 2D images is capturing 3D depth images. A depth imaging system has been applied to quantify static space usage of modern grow-finish pigs (Condotta et al., 2018). Distance between the animal and depth sensor can be calculated for each image individually, enabling more reliable conversion factors from pixels to physical measurements. Thus, to capture dynamic sow postural transitions accurately, application of a depth imaging system is necessary.

Static and dynamic space usage of gestating sows have not been recently evaluated; albeit, advances in swine genetics have changed the size of commercial sows. Developments in technology such as depth sensors allow accurate and automated assessment of sow space usage. The objectives of this work were:

(1) develop the relationship between pixel and physical measurements using a Kinect V2® time-of-flight depth sensor (Microsoft, Redmond, WA, USA), (2) quantify the static and dynamic space usage of modern commercial sows in late gestation when housed in an open pen, and (3) develop a statistical model relating sow body weight to static and dynamic space usage. This information is expected to enable an improved understanding of modern sow space usage and inform guidelines for individual sow gestation stall dimensions.

MATERIALS AND METHODS

SENSOR CALIBRATION

A calibration procedure and regression analysis determined the relationship to convert pixel measurements to physical dimensions (i.e., centimeters), as well as compensated for potential distortion induced by the time-of-flight depth sensor. One Kinect V2® was suspended from the ceiling in a laboratory setting to capture depth images. Rigid foam insulation (19 mm thick) was used to create calibration rectangles of various dimensions to simulate sow size. Calibration rectangles were individually placed in multiple configurations within the viewable area of the Kinect V2® to develop
the calibration regression equation.

Calibration rectangle widths (50, 60, and 70 cm) were selected based on the most common U.S. gestation sow stall width (60 cm) and were varied to encompass a ±10 cm range (Midwest Plan Service, 1983). Preliminary manual measurements of sow length ranged from 150 to 190 cm; thus, the calibration rectangle lengths (150, 170, and 190 cm) were chosen to represent the anticipated range. Combinations of the three widths and three lengths resulted in nine sizes of calibration rectangles.

Data collection in the commercial facility would require mounting the Kinect V2® 218 cm above the floor (as constrained by ceiling height). Therefore, 218 cm was used as the maximum distance point between Kinect V2® and calibration rectangles during sensor calibration. The minimum calibration distance point was 127 cm, as determined by preliminary measurements of standing sow height. Additionally, a middle point of 173 cm distance between calibration rectangle and Kinect V2® was used.

Four locations within the viewable area of the depth image (middle, top edge, corner, and side edge) were tested to verify potential data distortion on the long axis (x-direction) and short axis (y-direction) of the image. The long axis of calibration rectangles was placed in two orientations: (1) parallel to the x-direction of the image, and (2) parallel to the y-direction of the image. In each configuration, the calibration rectangles were supported underneath at both ends and the middle to ensure the entire calibration rectangle was at a uniform height. Twelve depth images were taken of each possible configuration, six of which were randomly selected for analysis.

Combination of all factors yielded 216 possible configurations. In some cases, the entire calibration rectangle was not within the viewable area of the depth image of the Kinect V2®, thus, some configurations were excluded from analysis. All 150 usable combinations are shaded below in Table 1.
Table 1. Matrix of all possible calibration configurations with usable combinations shaded. Calibration rectangle width is designated by W (50, 60, and 70 cm), length is designated by L (150, 170, and 190 cm), orientation as long axis of the calibration rectangle parallel to the x- or y-direction of the image. Position within image indicated by P (C-corner, S-side, E-center, T-top). Distance from Kinect V2® to calibration rectangle indicated as D (218, 173, 127 cm)

<table>
<thead>
<tr>
<th></th>
<th>Long axis of calibration rectangle parallel to x-direction of image</th>
<th>Long axis of calibration rectangle parallel to y-direction of image</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W50</td>
<td>W60</td>
</tr>
<tr>
<td>D218</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td></td>
<td></td>
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<tr>
<td>P2</td>
<td></td>
<td></td>
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<td>P4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D173</td>
<td></td>
<td></td>
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<tr>
<td>P1</td>
<td></td>
<td></td>
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<td>P2</td>
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<td>P3</td>
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<td>P1</td>
<td></td>
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<td>P2</td>
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<td></td>
<td></td>
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<tr>
<td>P4</td>
<td></td>
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</tbody>
</table>

An algorithm developed in MATLAB (R2017a, The MathWorks, Inc, Natick, MA, U.S.) was used to process the depth images. The algorithm isolated the calibration rectangle in the image and calculated the maximum x and y measurements in pixels. Pixel measurements were divided by the actual calibration rectangle dimensions (measured with a tape measure) and this information was used to develop a regression to relate pixel to physical distance.

Animals

A total of 61 structurally sound Landrace × Yorkshire (PIC genetics) gilts and sows, hereafter all referred to as sows, in weeks 11 to 15 of gestation were observed in this study. Late gestation sows were selected because during this period the greatest body dimensions were expected. Each sow was weighed within seven days of image data collection. Two 22.7 kg certified calibration weights were used to confirm the accuracy of the scale at each weighing event. Sow body weight ranged from 169.2 to 281.2 kg with an average of 228.6 kg. Sows selected in this study were normally housed in gestation pens in groups of 12 to 15 sows or in individual gestation stalls.

Experimental Setup and Instrumentation

Two observation pens with fully slatted concrete floors housed individual sows during image data collection periods. The pen floor area was 1.8 × 2.5 m, which provided the sow space to turn around,
lay down, and stand up without touching the pen sides, if desired. Sows were placed in one of the
observational pens for 24 h and were fed once per day in their previous stall or pen per farm operating
procedures, immediately prior to observation. After observation, sows were moved to individual stalls.
One nipple drinker in each observation pen provided *ad libitum* water. Data were collected from January
2017 to December 2018, with an average room temperature of 19°C (SD = 2°C) and average relative
humidity of 68% (SD = 11%) as recorded by a portable datalogger (MX2300, Onset Computer
Corporation, Bourne, MA, U.S.) suspended above the observational pens.

One Kinect V2® sensor was suspended from the ceiling above the center of each observation pen and
was connected to a mini-PC (ZBOX-CI325NANO, ZOTAC, Duarte, CA, U.S.). Both depth and digital
images were collected at 0.5 FPS. Depth images (512 × 424 pixels) had a viewable floor area of 3.6 ×
2.9 m. Digital images (1920 × 1080 pixels) were collected solely for animal identification. Images were
stored on external hard drives for subsequent processing. One cellular mobile hotspot was connected to
both mini PCs to enable remote monitoring of data collection.

**Image Selection Criteria**

Measurements were performed on sows when observed to be in five unique positions. These five
positions were comprised of three static positions: static lying (SL), static full lying (SFL), and static
standing (SS) as well as two dynamic positions: dynamic laying down sequence (DLD) and dynamic
standing up sequence (DSU). Three images of each sow in the desired static position (lying, standing)
were manually selected, with the same images being used for SL and SFL. Static lying images were
chosen when the sow was recumbent, with at least three legs completely visible and head in profile
view. Preference was given to lying images with all legs visible and fully extended. For occurrences of
SS, three images were manually chosen when the sow was stationary and standing upright with legs
fully extended, nose pointed forward, and oriented reasonably straight from nose to tail. If possible,
images taken at various hours throughout the observation period were selected.

Three separate sequences were manually chosen for DLD and DSU. Delineation of beginning and
end of these sequences were modeled after descriptions provided by Baxter and Schwaller (1983). The DLD sequences began with one image of the sow standing upright, continued as she went to her knees in the kneeling position, and was completed with one image of the sow lying down. Conversely, DSU sequences began with one image of the sow laying, continued as she transitioned to sitting, and ended with one image of the sow standing upright. Dynamic sequences with duration less than 6 s were discarded to ensure at least one frame of transitional posture was captured. Sequences greater than 60 s were discarded as these longer sequences often encompassed additional behaviors outside the definitions of the transition sequences described above (i.e., extensive rooting, nosing other sows through the gating). Of the sequences that satisfied the selection criteria, final dynamic position choices were made to vary the hour of occurrence of the sequences throughout the data collection period for each sow.

**IMAGE PROCESSING**

A MATLAB program was used to isolate the sow in the depth images selected for analysis. First, distance measurements from the Kinect V2® were subtracted from 2.18 m (distance from Kinect V2® to pen floor) to establish height above the floor. Pixels with a height less than 20 mm were eliminated to remove the pen floor and other noise. Gradually increasing height filters were applied to the edges of each image to remove the pen walls and drinker. The largest blob remaining in the image was then selected as the sow, effectively eliminating manure or other objects from the image. Average height of all pixels in the sow blob was calculated in each depth image. The outline of the sow blob was converted to a polygon and then scaled from pixel to physical measurements utilizing the calculated conversion factor based on the average height of all pixels in the sow blob. Scaled polygons were then binarized.

For static positions, length and width parameters were measured from the binary sow blob using a bounding box. Static full lying, SFL, evaluated the total space occupied by the sow with width measured from the back of the sow to the end of the fully extended legs (Figure 1). Alternatively, SL evaluated the space occupied by the sow based on the assumption that legs of a fully recumbent sow will extend
into a neighboring stall; therefore, the SL bounding box excluded the extended legs (i.e., region extended past the elbow and hamhock) and the width was measured from the back of the sow to the udder line. Length and width measurements were also taken on the bounding box for the SS position (Figure 1).

**Figure 1.** Example illustrations of postural positions assessed in this study with bounding boxes drawn in red to show the length and width of measurements. Height was also measured but excluded from this figure for clarity. Images are not to scale. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

For dynamic positions, each image of the sequence was scaled and binarized with the same process as the static images. Polygons were scaled around the centroid of the sow in each image. All images in a dynamic sequence were superimposed to determine the maximum space utilization for the sequence (Figure 1).

In both the static and dynamic analyses, it was assumed the ears and tail of the sows were flexible and could fit within the bounding box created by the bulk of the sow body. If these body parts were the maximizing pixels in any dimension of the bounding box, they were cropped from the image. The length and width of the bounding box utilized for each posture or transition were measured, as well as the maximum single pixel height.

**Statistical Analysis**

Statistical analysis was conducted using R statistical software with car, emmeans, lmerTest, and stats packages (Fox and Weisberg, 2019; Kuznetsova et al., 2017; Lenth, 2019; R Core Team, 2019).
natural log transformation was performed on the response variables, that is, bounding box length, width, and height, as well as the variable of sow weight to correct trends in model residuals. Then, for a given sow and position, the three repeated measurements were averaged for each response dimension. As some of the response dimensions showed evidence of correlation, the length, width, and height for each position were analyzed simultaneously using a multivariate analysis of variance (MANOVA). Sow parity, weeks in gestation, and transformed sow weight were used as variables. Observational pen was included as a covariate as pen representation was unbalanced due to data collection failures (9 sows from observation pen A, 52 sows from observation pen B). Date of data collection was excluded from the model as multiple sows were observed on only 4 of the 57 days of data collection.

**RESULTS AND DISCUSSION**

**SENSOR CALIBRATION**

Regression equations were calculated using the x-, y-, and combined x- and y-directions and are shown in Table 2. The combination x- and y-direction regression resulted in minimal impact on conversion accuracy, so both directions were combined for simplicity. The RMSE of this equation resulted in an uncertainty of 0.013 m.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Adjusted R²</th>
<th>RMSE (m)</th>
<th>Number of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-direction</td>
<td>(139.7d^2-617.7d+854.7)</td>
<td>0.9994</td>
<td>0.01277</td>
</tr>
<tr>
<td>y-direction</td>
<td>(142.1d^2-627.3d+864.7)</td>
<td>0.9996</td>
<td>0.01123</td>
</tr>
<tr>
<td>x- and y-direction combined</td>
<td>(140.9d^2-622.5d+859.7)</td>
<td>0.9995</td>
<td>0.01282</td>
</tr>
</tbody>
</table>

The residual error of the pixel m⁻¹ versus distance from Kinect V2® equation is shown in Figure 2. One outlier was excluded. A quadratic regression was selected as it explained the greatest amount of variation in the data. An increase in variation was observed with increasing distance from the Kinect V2®, as the depth sensor becomes noisier with increased distance (Steward et al., 2015). This variation subsequently increased the range of residuals at greater depth distances.
Figure 2. Pixel m⁻¹ versus distance from Kinect V2® equation and residuals (actual – predicted).

An evaluation of residuals indicated that there were no obvious trends associated with calibration rectangle length, width, orientation, distance from sensor, or location within image. Depth information output from the Kinect V2® is inherently in millimeters, and thus did not require a conversion equation. Distance measurement errors due to sow height, orientation, and position within the depth image are negligible (Wasenmüller and Stricker, 2017).

CORRELATION BETWEEN LENGTH, WIDTH, AND HEIGHT OF SOW MEASUREMENTS

There was evidence of correlation between dimension measurements of sows for some of the positions observed, with the greatest correlation occurring between the length and height for standing sows (r = 0.45; Table 3). This evidence was used to justify the use of MANOVA. In all positions, dimension responses were significantly influenced only by sow weight (p<0.001 for each model). As such, result presented below are averaged over sow parity, weeks in gestation, and pen.
Table 3. Correlation coefficients between length, width, and height for each of the five positions measured. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

<table>
<thead>
<tr>
<th>Position</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL</td>
<td>0.069</td>
<td>0.041</td>
</tr>
<tr>
<td>SFL</td>
<td>0.121</td>
<td>0.023</td>
</tr>
<tr>
<td>SS</td>
<td>-0.043</td>
<td>0.449</td>
</tr>
<tr>
<td>DLD</td>
<td>0.085</td>
<td>0.266</td>
</tr>
<tr>
<td>DSU</td>
<td>0.221</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Table 4. Equations relating sow body weight (W) in kg to dimensions of space usage for given positions. Results are presented with ± percent SE when possible. The results from the present study are shown in conjunction with equations from previous literature. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

<table>
<thead>
<tr>
<th>Position</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Source</th>
<th>Animals</th>
<th>Sow BW Range (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL</td>
<td>430W0.26±0.45%</td>
<td>279W0.17±0.45%</td>
<td>161W0.15±1.50%</td>
<td>Present Study</td>
<td>61 sows</td>
<td>169.2-281.2</td>
</tr>
<tr>
<td>SFL</td>
<td>465W0.24±0.45%</td>
<td>298W0.21±0.63%</td>
<td>156W0.16±1.51%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>585W0.18±0.46%</td>
<td>97W0.27±0.65%</td>
<td>217W0.25±0.55%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLD</td>
<td>360W0.29±0.65%</td>
<td>165W0.30±1.06%</td>
<td>560W0.08±0.65%</td>
<td>Baxter and Schwaller (1983)</td>
<td>191 pigs</td>
<td>1-286</td>
</tr>
<tr>
<td>DSU</td>
<td>557W0.23±0.58%</td>
<td>5460W0.30±2.01%</td>
<td>557W0.23±0.69%</td>
<td></td>
<td>10 sows</td>
<td>210-215</td>
</tr>
<tr>
<td>Static Standing</td>
<td>297W0.33±4.06%</td>
<td>59W0.34±6.28%</td>
<td>166W0.29±4.71%</td>
<td>Curtis et al. (1989)</td>
<td>208 sows</td>
<td>161.4-343.2</td>
</tr>
</tbody>
</table>

Graphical depictions of the relationship between sow weight and static/dynamic space usage are presented in Figure 3. Corresponding allometric equations are shown in Table 4, as well as equations presented in other studies. The greatest variation was seen in bounding box width for the DSU position, and this variation is likely the source of the negative correlation between weight and width dimension.

For the static positions, a sow at a given weight had a decrease in length for SS compared to SL or SFL. This decrease could be caused by the differences between postures as the sow may adopt a greater back curvature when standing; thus, reducing body length.

Table 4. Equations relating sow body weight (W) in kg to dimensions of space usage for given positions. Results are presented with ± percent SE when possible. The results from the present study are shown in conjunction with equations from previous literature. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

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RELATIONSHIPS BETWEEN SOW WEIGHT AND SPACE USAGE

Graphical depictions of the relationship between sow weight and static/dynamic space usage are presented in Figure 3. Corresponding allometric equations are shown in Table 4, as well as equations presented in other studies. The greatest variation was seen in bounding box width for the DSU position, and this variation is likely the source of the negative correlation between weight and width dimension.

For the static positions, a sow at a given weight had a decrease in length for SS compared to SL or SFL. This decrease could be caused by the differences between postures as the sow may adopt a greater back curvature when standing; thus, reducing body length.
Figure 3. Relationship between sow body weight and length, width, and height of space usage for each position. Shading indicates 95% confidence interval. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

For a static position linear dimension should vary with volume or weight to the one third power (Baxter and Schwallier, 1983; Thompson, 1917). The empirical equations developed in this study for SS most closely meet this expectation. The exponent for SS length is lower than the anticipated one third value, indicating that sow body weight has a smaller influence on length. The coefficients are similar between SL and SFL, with the marked difference being the decrease in exponent for SL width due to the exclusion of the space occupied by the legs of the sow. Values fluctuate for coefficients and exponents of the dynamic sequences. The negative exponent and large coefficient for DSU width are likely due to the variation seen in these sequences. Comparisons between sow dimensions for specific body weights will be discussed in the following section.

For all positions and sow weights evaluated, the height of the space utilized by sows was less than the typically provided 100 cm gestation stall height (Midwest Plan Service, 1983). Though the length of space utilized by sows in this study was less than typical stall dimension of 213 cm, it is important
to consider other behaviors sows must perform when housed in stalls. Additional stall length may be
needed for defecation and urination, and some manufacturers place feeders within the stated outer
dimensions of stalls. The quality of the space provided (i.e., flooring type, partition type, enrichments)
can influence how sows use the space as well (Baxter et al., 2011). These aspects should be considered
and further investigated before modifying the stall length from the current typical recommendation of
213 cm.

In this study, the width of space usage only in the SS position was less than the typical gestation stall
width of 61 cm (Midwest Plan Service, 1983). When lying, average sow depth of body ranged from 67
cm (169 kg sow) to 73 cm (281 kg sow). Width of space used was increased further in the dynamic
sequences, suggesting that gestation stalls may restrict sow space usage compared to open space.

For each dimension of length, width, and height the greatest values and greatest variation occurred
in the standing up sequences. Baxter and Schwaller (1983) also found the standing up sequence to
require the greatest amount of space, and attributed the large variation in this movement to differences
in sow stability due to individual clumsiness and flooring condition.

**STALL SIZE RECOMMENDATIONS**

Relationships observed between sow weight and space usage indicate stall size recommendations
should be based on sow weight. To better accommodate sow and financial limitations, it is reasonable
to propose two different sizes of sow stalls. Table 5 displays the space usage by dimension utilized by
average body weight sows, 228 kg, and 95th percentile of sow weights in this study, 267 kg. Values are
presented with 95% confidence intervals. Gestation stalls should accommodate the positions measured
in this study; therefore, stall sizes are based on the greatest dimension value (DSU position). Similar to
recommendations made by McGlone et al. (2004), stall dimensions are proposed to include the upper
limits of the 95% confidence interval. Hence, a stall size to accommodate small to average sows based
on space usage would need minimum dimensions (L × W × H) of 196 × 115 × 93 cm. A stall size to
accommodate average to 95th percentile sows would be 204 × 112 × 95 cm. While these direct study
recommendations would suggest that larger sows require a decrease in stall width, when the amount of
variation is considered, it is not recommended to decrease stall width for larger sows.

Table 5. Length, width, and height of mean space usage and 95% confidence interval are provided for each position measured for an average (228 kg) and a 95th percentile sow (267 kg). Largest values for each dimension are in bold. Static positions: SL – static lying (excluding extended legs), SFL – static fully lying (including extended legs), SS – static standing. Dynamic positions: DLD – dynamic laying down, DSU – dynamic standing up.

<table>
<thead>
<tr>
<th>Body Weight</th>
<th>Position</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>95% CI</td>
<td>Average</td>
</tr>
<tr>
<td>Average sow, 228 kg</td>
<td>SL</td>
<td>171.6</td>
<td>[168.4, 174.8]</td>
<td>70.8</td>
</tr>
<tr>
<td></td>
<td>SFL</td>
<td>172.9</td>
<td>[169.4, 176.4]</td>
<td>92.5</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>157.4</td>
<td>[154.2, 160.6]</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td>DLD</td>
<td>175.4</td>
<td>[170.3, 180.5]</td>
<td>82.7</td>
</tr>
<tr>
<td></td>
<td>DSU</td>
<td>190.5</td>
<td>[185.4, 195.6]</td>
<td>106.4</td>
</tr>
<tr>
<td>95th percentile sow, 267 kg</td>
<td>SL</td>
<td>178.7</td>
<td>[174.4, 183.0]</td>
<td>72.8</td>
</tr>
<tr>
<td></td>
<td>SFL</td>
<td>179.7</td>
<td>[175.0, 184.4]</td>
<td>95.6</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>162.0</td>
<td>[157.7, 166.3]</td>
<td>43.9</td>
</tr>
<tr>
<td></td>
<td>DLD</td>
<td>183.7</td>
<td>[176.8, 190.6]</td>
<td>86.7</td>
</tr>
<tr>
<td></td>
<td>DSU</td>
<td>197.4</td>
<td>[190.6, 204.2]</td>
<td>101.5</td>
</tr>
</tbody>
</table>

Compared to other literature, late gestation sows measured by Curtis et al. (1989) were heavier than those observed in this study with a mean sow weight of 244.8 kg and 95th percentile of 304.5 kg compared to 228 and 267 kg in this study. However, all the sows assessed by Curtis et al. (1989) were in week 15 of gestation and parities 1 through 9 were included. Compared to this study, weeks of gestation ranged from 11 to 15 and the highest parity was 8. Results from this study are similar to average measurements of length, width, and height for standing sows as measured by Curtis et al. (present study: 159.5, 42.9, 87.9 cm; Curtis et al.: 160.8, 42.9, 89.2 cm). Sow depth of body was not measured by Curtis et al. (1989), thus this measurement, thought to be an increased dimension for modern sows, could not be compared. Further, Curtis et al. (1989) estimated dynamic space usage with allometric equations proposed by Baxter and Schwaller (1983) and found that a 250 kg sow would require 220 × 86 × 99 cm stall. Comparatively, the use of models developed in this study indicate that a 250 kg sow would require a 195 × 104 × 91 cm stall. The use of the empirical data collected here results in an 11% decrease in stall length, 21% increase in stall width, and an 8% decrease in stall height.
to accommodate free choice sow space usage.

McGlone et al. (2004) also measured heavier sows in comparison to the present study (average: 239.9 kg, 95th percentile: 332.7 kg). Comparatively, data from the present study suggests modern sows of a given weight have a 7% decrease in length, 7% increase in width, but remain similar in height when standing (present model: 159, 43, 87 cm; McGlone et al.: 171, 40, 88 cm). The average depth of body reported by McGlone et al. (2004) was 13 cm less (22% difference) than predicted by the current model (current model: 71 cm; McGlone et al.: 58 cm), suggesting that modern sows do have increased depth. However, it is important to note that measurements reported by McGlone et al. (2004) were taken on standing sows while the current model measured depth of body on lying sows.

More recently, Mumm et al. (2019) cited that sows in week 13 of gestation required 1.26 and 1.37 m² to lay down and stand up, respectively. However, no sow weights were presented with these measurements and only one sequence of each transition was measured per animal. Moreover, only one calibration image was collected to convert from pixel to physical measurements. It is important to note that the space usage reported by Mumm et al. (2019) is the projection of the floor area occupied by the sow and not the dimensions of the stall needed to house the sow as reported in this study.

Gestation stall size is a function of numerous factors and space usage for turning around should be considered. Turning around in stall housing is undesirable as it can present management and hygiene concerns. The stall width needed for a sow to turn around is often assumed to be length of sow body, but Bøe et al. (2011) reported that 7 out of 16 mid-gestation sows observed could turn around in stalls with a width 50% of their own body length. Based on the sow weights in this study, 50% of body length when standing would range from 75 to 82 cm. It is not uncommon for commercial sows to be able to turn around in traditional gestation stalls with a width of 61 cm, suggesting that space requirements for turning around may also depend on sow flexibility and motivation. Further information is needed on this topic.

Current gestation stall width is less than the width of space used by gestating sows in this study,
implying that sows may be limited when lying recumbent and performing dynamic postural transitions in gestation stalls. However, it is unclear what amount of restriction results in a negative change in animal welfare. It has been shown that reducing pen width from 240 m to sow body length results in significant changes in frequencies of turning around, but statistical differences in time spent lying were not detected until pen width was reduced to 60% of sow body length (Bøe et al., 2011). Anil et al. (2002) determined that duration of time spent in postural positions and time required for postural changes were influenced by stall length and width relative to sow length and breadth. These results suggest that space restriction can lead to alterations in sow behavior. Additional experiments are needed to determine the relationship between amount of space restriction and sow welfare.

CONCLUSIONS

A computer vision system was developed using a 3D time-of-flight sensor to accurately measure the static and dynamic space usage of 61 modern commercial sows in late gestation. A thorough calibration was conducted to convert pixel measurements to physical measurements based on the height of the sow. Using this information, the length, width, and height of a bounding box occupied by the sow were evaluated for five sow positions (static: lying, full lying, standing; dynamic: laying down sequence, standing up sequence). Models were developed to relate dimensions of space usage to sow weight. Average sow (228 kg) static and dynamic postural transitions minimum space usage was \((L \times W \times H)\) 196 \times 115 \times 93\ cm. A 95th percentile sow (267 kg) space usage was 204 \times 112 \times 95\ cm. This information offers an improved understanding of modern sow space usage and can be used to inform guidelines for individual sow gestation stall dimensions. Further work is needed to obtain sow space usage for turning around and to evaluate the impact of varying space restrictions on sow welfare.

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