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Special Topics

Height relative to body weight in nursery pigs

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Abstract

Among the physical dimensions of the pig body, the height has received limited scientific focus. During transport, however, where multideck trucks and trailers typically are used, detailed knowledge about the height of pigs is relevant. The body weight of pigs is often known, whereas height is more difficult to quantify as part of the pre-transport management of the pigs. Nursery pigs are one category of European pig production often subjected to long distance transport for further fattening some weeks after weaning. The present study aimed to determine the height of pigs from 5 to 40 kg of body weight, as well as the relation between height and body weight. The height and weight were measured for 1,614 randomly selected pigs (castrates and females) from 10 Danish pig herds balanced between the two large breeding systems, DanBred (**DB**) and Danish Genetics (**DG**). From 9 herds, data from 1,435 pigs with 2.8 to 40.6 kg body weight were used for establishing prediction equations, while pigs from the tenth herd were set aside for validation.

The study considered using 1) polynomial regressions of various order; 2) power functions; or 3) nonlinear growth curve models. Overall, the third-order polynomial with sex-specific intercept and the power function with sex-specific log-intercept were optimal for prediction. Nevertheless, for feasibility and due to only marginal sex differences, we suggest using common intercepts for prediction of height from weight. Taken together, the results of the present study present data for pig height in the interval from 5 to 40 kg body weight. Further, we suggest that a third-order polynomial or a power function can be used for pigs from at least the genetic systems DB and DG, if the pig height is to be predicted based on body weight.

Lay Summary

Among the physical dimensions of the pig body, the height has received limited scientific focus. However, during transport, where multideck trucks and trailers of limited deck height typically are used, detailed knowledge about the height of pigs is relevant. One pig category often subjected to long distance transport in Europe is nursery pigs, transported for further fattening some weeks after weaning. The body weight of pigs is often known, whereas height is more difficult to quantify as part of the pre-transport management of pigs. To determine the relation between body weight and height for this category of pigs, a total of 1,614 castrates and female nursery pigs from 10 different Danish herds with pigs from one of two larger Danish breeding systems (DanBred or Danish Genetics) were measured. A third-order polynomial and a power function were determined and can be used to predict pig height from weight for pigs in the range from around 5 to 40 kg.

Key words: height, pigs, transportation, weight

Abbreviations: DB, DanBred; DG, Danish Genetics; *H*, height, cm; MAE, mean absolute error; *P*, distance from plexiglass plate to the highest point over the back hips of the pig, cm; R^2, coefficient of determination; RMSE, root mean squared error; *S*, distance from the plexiglass plate to the bottom of the scale, cm; *W*, weight, kg

Introduction

In Europe, large numbers of pigs are transported long-distance for further fattening some weeks after weaning (Dahl-Pedersen and Herskin, 2021) by use of multideck trucks and trailers with deck height of approximately 60 to 70 cm. The European Regulation (EC, 1/2005) states that the height provided in means of transport should be appropriate to the size of the animals and the intended journey and that adequate ventilation, when animals are in a natural standing position, should be offered without on any account hindering the natural movements of the animals. Specific deck height requirements are not given for pigs. EFSA (2002) recommended a deck height of at least 15 cm above the pigs in mechanically ventilated trucks, and at least 30 cm when only passive ventilation is possible. More recently, The Consortium of the Animal Transport Guides Project (2017) considered it to be good practice to transport pigs in the weight interval of 10 to 25 kg at a deck height of 62 cm, but no scientific evidence was presented to support this recommendation.

Animal height is an important factor when appropriate deck height for transport is decided. However, so far, the scientific focus on height of pigs has been rather limited as only few references dating decades back exist, and often with limited focus on the weight interval relevant to nursery pigs (e.g., Vorup and Barton-Gade, 1991; Brandl and Jørgensen, 1996). In addition, as argued by Condotta et al. (2018), improved and new genetic lines as well as knowledge about nutrition and feed increase the relevance of an update and validation of the bodily dimensions of modern pigs. Based on measurements made by image analysis of 150 pigs of 4 to 20 weeks of age, Condotta et al. (2018) concluded that the pigs were approximately 5% lower in height than reported from

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standards published in 1968. The aim of the present study was to determine height of pigs in the weight interval from 5 to 40 kg of body weight and to establish new or confirm the validity of currently used equations for the prediction of height from body weight in this weight interval.

Materials and Methods

Animals

The study included 1,614 pigs from 10 Danish pig herds with production of castrated and female nursery pigs (Table 1). Data were collected from October 22, 2020, to February 17, 2021. All participating herds adhered to the institutional animal care according to the Danish standards and the legislation for pig production. The pigs were selected from a total of 320 pens in 88 so-called sections (i.e., rooms with pens for nursery pigs).

The herds were selected based on an aim to balance between the two major breeding systems in Denmark [DanBred (**DB**) and Danish Genetics (**DG**), both of which derive from the former DanAvl pig breeding system], assuming that approximately 2/3 of the Danish pig producers buy their gilts, whereas 1/3 breed their gilts ('homebreeders'). Nevertheless, as DG at the time of the study had been an independent company for only two years, it was not possible to identify herds that bred their own DG gilts. Therefore, the "home breeder" type of herd was only represented by the DB breeding system. The origin of semen was not taken into account when the herds were selected. Thus, the 10 herds consisted of 2 herds purchasing DG gilts and DB semen, 2 herds purchasing DG gilts and DG semen, 3 herds purchasing DB gilts and DB semen, and 3 DB "home breeders" who purchased DB semen. Eight out of the 10 herds weaned nursery pigs each week. The remaining two herds were weaned every 14 d. The herds were recruited through a major Danish distributor of boar semen by convenience sampling but with the aforementioned balance in mind.

The first herd recruited was used for pilot studies and testing of procedures. Once settled, a final sampling was carried out along the same lines as used for the other herds. Data from this herd were used for external validation of the prediction equations developed by the use of data from the other nine herds. At the first herd, weaning took place weakly, gilts were bought from the DG breeding program, and semen from DB.

Within herds, all pigs used for data collection were selected at random according to the following procedures. Initially, a predetermined number of pens were randomly drawn from each available section, ensuring good coverage across ages, and thus weights and heights. Prior to visiting the herd, a number of backup-pens were randomly chosen from each section (depending on section size). These pens were included if a planned pen could not be used (e.g., was empty on the day of sampling). Efforts were made to only visit the herds when all sections in the nursery part of the herd were expected to be full. In most herds, eight sections were available (range: 8 to 11) and measurements were made on pigs from an average of 32 pens (range: 30 to 34) from each herd (Table 1).

In each of the randomly selected pens (typically housing approximately 35 pigs, but with some variation), an observer entered the pen, made sure that pigs were active, and marked the initial 10 pigs encountered with numbers from 1 to 10. Out of these 10 pigs, 5 pigs were selected following a list of randomly ordered numbers from 1 to 10. The height and weight data were collected over two consecutive days. For each pig involved in the study, the sex was determined. Four entire male pigs and one without sex determined were excluded from the study, leaving only castrates and females for the modeling.

Data collection

Pigs to be measured were entered into a single animal scale suitable for their weight category (0301GE single animal scale, Bjerringbro Vægte ApS, Bjerringbro, Denmark). For biosecurity reasons, each scale had to be returned to the producer of the scale for cleaning and disinfection before it could enter new herds. During this process, the producer calibrated the scales. The weight of each pig was read once, and the height was calculated as the average of three subsequent measurements.

After a small pilot study, it was assessed that the highest point over the back hips of a pig was the most appropriate point for height measurement, which also corresponds to the measuring point used in previous studies focusing on pig height (Vorup and Barton-Gade, 1991; Brandl and Jørgensen, 1996) as it is the highest spot on a standing pig. To ensure

Table 1. Characteristics of 10 herds that were used to study the height of nursery pigs

Herd	Size[1]	Nursery pigs	Operation	Breed[2]	Gilts	Semen[2]	Sections[3]	Pens[3]
1	930	4,500	Weekly	DG	Buying	DB	8	32
2	1,315	6,500	Weekly	DG	Buying	DB	8	32
3	620	3,000	Biweekly	DB	Homebred	DB	8	32
4	845	6,100	Weekly	DG	Buying	DG	8	32
5	2,800	10,000	Weekly	DB	Buying	DB	8	32
6	4,000	7,000[4]	Weekly	DG	Buying	DG	8,	32
7	1,200-	5,800	Biweekly	DB	Homebred	DB	11	33
8	1,200	5,500	Weekly	DB	Buying	DB	8	34
9	2,100	8,500	Weekly	DB	Homebred	DB	10	31
10	1,700	8,000	Weekly	DB	Buying	DB	11	30

[1]Sows, gilts, and boars
[2]DG ,Danish Genetics (https://danishgenetics.dk/en/), DB, DanBred (https://danbred.com/).
[3]Sampled for this study.
[4]On three locations.

the greatest possible uniformity during data collection, this anatomical location was identified on each pig by drawing a fictitious vertical line beginning at groin folds (Figure 1a) and ending on the highest point over the back hips. The measuring point was marked with a black wax crayon as shown in Figure 1b. While the pig was inside the scale, a transparent plexiglass plate (PLEXIGLAS, Röhm GmbH, Darmstadt, Germany; 74 × 35 × 0.5 cm) was placed over the pig using the fixtures of the scale as a shelf. By placing a laser distance meter (Leica DISTO X3, Leica Geosystems AG, Heerbrugg, Switzerland) perpendicularly on top of the plexiglass plate, the distances from the plexiglass plate to the bottom of the scale (**S**) and to the measuring point on the pig (**P**) were measured. The height (**H**) of the pig was then calculated by subtracting these two distances, corresponding to $H = S - P$. Each experimental pig was only handled once on the scale and measured while standing as calmly as possible in a natural position. To retrieve quantification of pig height in triplicate, the laser distance meter was removed from the plexiglass plate between successive measurements of the distance P. The distance S was determined as the average of three successive measurements, repeated for each section in the nursery part of each herd. For biosecurity, when brought into different herds, the laser distance meter was wrapped in a plastic bag (Minigrip Sample bags with writing area 180 × 120 mm, Minigrip, Alpharetta, GA). Potential effects of the bag were not examined, but the same type of bag was used in all herds. The distance meter was not calibrated during the study.

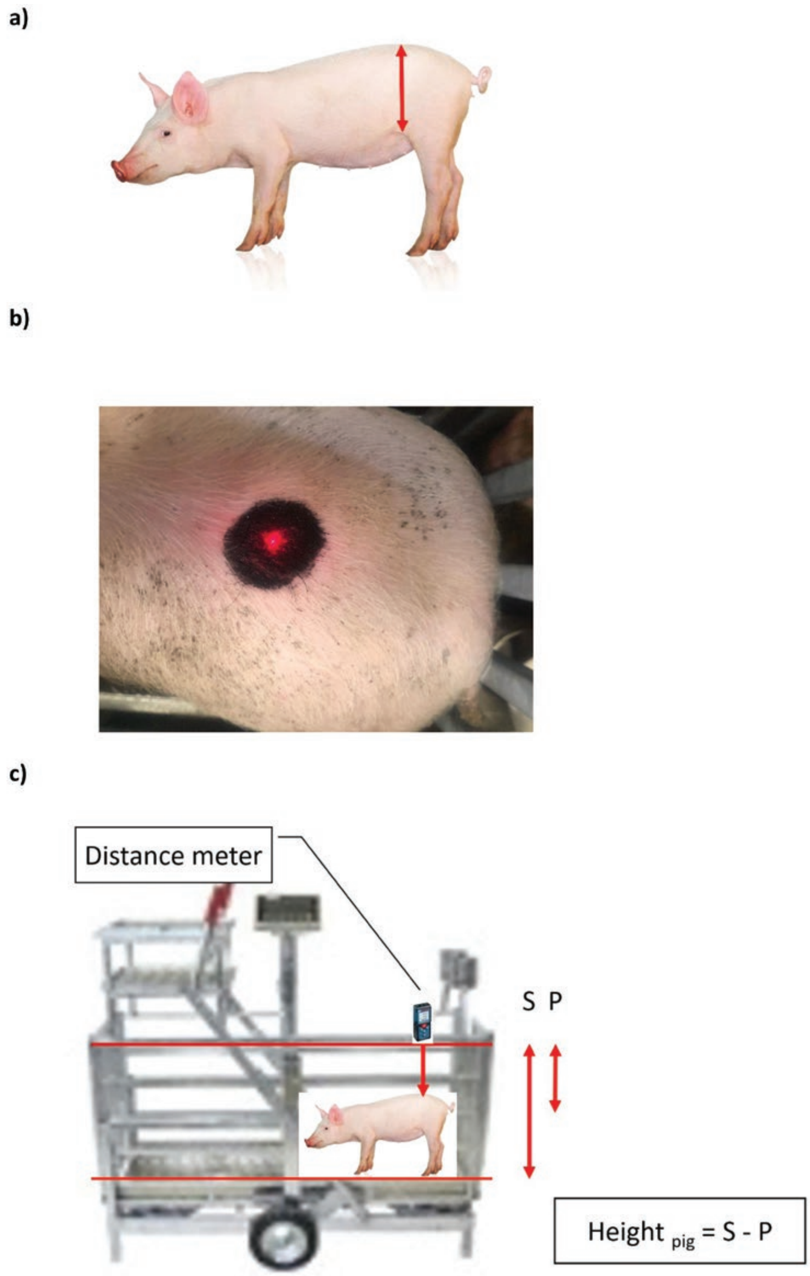

Figure 1. Practical method for measuring pigs' height using a distance meter. (a) Vertical line (red arrow) from a pig's groin fold to the highest point over the back hips to identify the location at which height was determined. (b) Marking point (black spot) on the highest point over the back hips of a pig. The red spot is light from a laser distance meter. (c) Method used to calculate pig's height using a distance meter.

Statistical methods

On the basis of herds 2 to 10 (training data) we developed prediction equations aimed at nursery pigs up to a weight of about 40 kg. The pigs used for building these equations weighed from 2.8 to 40.6 kg (Table 2). Three different types of models were considered; 1) polynomial regressions of various order, 2) power functions obtained by exponentially back-transforming log-linear models, and 3) nonlinear growth curve models. Since the pigs were in a growing phase of life, even when considering the upper end of the weight range, horizontal asymptotes on the right side (large weights) are unlikely to have been reached yet. Nevertheless, polynomial models are also only realistic within the observed range of weights. Inclusion of herd characteristics (Table 1) and sex of the pig was examined. In the polynomial regressions, interaction between sex and (powers of) weight was also tested to investigate if sex-specific curves would fit best. Time since weaning was only known for approximately half of the pens and thus could not be included. This obvious confounder was, however, highly correlated with both height (Pearson's correlation coefficient, ρ = 0.84) and weight (ρ = 0.81), and in practical applications perhaps not that useful. Even at herd section level, average time since weaning could only be obtained for 61% of the sections in the present study. Thus, time since weaning was not examined further.

During model building, herd could be seen as a random effect, with the herds representing the population of Danish herds (using DG or DB breeds). Section (nested in herd) appeared an obvious choice as a second level of random effect, as pigs from the same section were both physically in the same room and of more or less same age. However, the simultaneous inclusion of both random effects resulted in singular fit of the herd effect (i.e., close to zero) in the polynomial models and we therefore only kept section nested in herd. In addition, correlation among pigs from the same pen would be anticipated for several reasons; siblings, size sorting, and same environment. The final predictions were made on population level, i.e. based only on the fixed effects estimates.

In this setting, the polynomial regression models of H as a function of weight ($\mathbf{W}$) were linear mixed effects models in the following form:

$$H_{ijkl} = \beta_0 + \sum_{q=1}^{Q} \left\{ \beta_q W_{ijkl}^q \right\} + \gamma X + \eta_{j(i)} + \varepsilon_{ijkl} \quad (1)$$

where i was an index for herd, j index for section (within herd), k index pen (of section in herd) and $l = 1, \ldots, n_{ijk}$ were the pigs measured in pen k of section j in herd i. Fixed effects parameters were the intercept β_0 and the coefficients β_q, $q = 1, \ldots, Q$, where Q was the polynomial order. Other potential fixed effects factors, covariates, or interactions were indicated by the row vector γ. The matrix X was the design matrix corresponding to these other variables, e.g., breed and sex. Obviously, the intercept was not really meaningful as a pig of weight zero is nonsense. Centre scaling to some meaningful weight could be a way to give the intercept meaningful interpretation but was not as such of interest in the present study. The random effect η of section within herd and the residual error ε were assumed normal distributed with zero mean. In addition, we included compound symmetry correlation within pen, i.e., $cor\left(\varepsilon_{ijkl}, \varepsilon_{ijkl'}\right) = \rho$ for two pigs l and l' from the same pen and $\rho = 0$ for pigs from different pens.

The second type of model was based on a linear regression of log(height) on log(weight)

$$\log\left(H_{ijkl}\right) = \beta_0 + \beta_1 \log\left(W_{ijkl}\right) \quad (2)$$

followed by an exponential back-transformation, which led to a power function

$$H_{ijkl} = f_P\left(W_{ijkl}\right) = \exp\left(\beta_0\right) W_{ijkl}^{\beta_1} = \alpha W_{ijkl}^{\beta} \quad (3)$$

Note that the derived parameter $\alpha > 0$ ensured a strictly positive height (for positive weight) even in the unrealistic case of a negative intercept in Eq. 2. The function in Eq. 3 would be strictly increasing if $\beta > 0$, strictly decreasing if $\beta < 0$ and constant ($= \alpha$) if $\beta = 0$. To estimate this model type, we used

Table 2. Summary statistics on weight and height data obtained from 10 different nursery herds

		Weight, kg					Height, cm				
Herd	N	Min–max	Avg.	SD	Med	Q1–Q3	Min–max	Avg.	SD	Med	Q1–Q3
1[1]	179	4.7 to 46.0	19.8	10.34	16.5	10.8 to 27.4	24.1 to 57.2	38.7	7.54	37.4	32.8 to 44.8
2	159	3.5 to 37.6	16.4	9.67	14.7	7.5 to 25.7	21.2 to 55.2	36.3	8.72	36.0	28.2 to 44.6
3	161	4.0 to 40.6	23.1	11.64	22.9	11.4 to 35.0	22.1 to 53.8	40.2	8.61	41.9	33.3 to 47.2
4	158	4.2 to 35.2	14.4	7.99	11.4	7.6 to 20.8	22.0 to 48.3	34.5	7.33	33.2	27.8 to 40.9
5	160	3.9 to 38.5	14.1	8.89	11.6	6.0 to 20.1	19.3 to 50.9	34.0	7.95	34.0	26.9 to 40.2
6	160	3.6 to 36.9	17.3	8.66	17.2	9.4 to 24.8	21.4 to 50.4	37.5	7.86	39.2	31.4 to 44.8
7	165	3.0 to 35.0	13.4	9.01	9.7	6.0 to 20.4	19.4 to 49.7	33.3	8.49	32.0	26.2 to 40.5
8	169	8.2 to 32.7	20.7	6.11	20.9	15.7 to 25.9	27.5 to 49.5	40.6	4.99	40.7	37.3 to 44.9
9	155	3.1 to 34.1	13.8	7.91	10.7	7.4 to 20.4	20.4 to 49.4	34.3	7.07	33.7	28.8 to 41.1
10	148	2.8 to 33.9	16.7	9.42	20.4	6.6 to 24.1	19.3 to 50.0	36.4	9.17	41.4	27.3 to 44.0
2 to 10[2]	1435	2.8 to 40.6	16.7	9.43	15.6	7.9 to 24.4	19.3 to 55.2	36.4	8.25	37.0	28.8 to 43.5

[1]Validation herd.
[2]Training herds.

the model of Eq. 1 with log-transformed heights and weights, and $Q = 1$.

The third type of model was based on a nonlinear mixed effects model. Three different three parameters growth models were examined: asymptotic (A), Gompertz (G), and logistic (L). The function relating height to weight used for the asymptotic model was

$$f_A\left(W_{ijkl}\right) = \beta + (\alpha - \beta)\exp\left(-W_{ijkl}e^{-\gamma}\right) \quad (4)$$

where β was the limit with increasing weight, α was the height when the weight was zero and γ was a numeric parameter representing the natural logarithm of the rate constant. The function used for the Gompertz model was

$$f_G\left(W_{ijkl}\right) = \beta exp(-\alpha\gamma^{W_{ijkl}}) \quad (5)$$

where β was the limit with increasing weight, α was related to the height when the weight was zero and γ was a scale parameter. Finally, the function used for the logistic model was

$$f_L\left(W_{ijkl}\right) = \beta/\left(1 + \exp\left(\left(\alpha - W_{ijkl}\right)/\gamma\right)\right) \quad (6)$$

where β was the limit with increasing weight, α was the weight at the inflection point of the curve where the height would be $\beta/2$, and γ was a scale parameter. In these nonlinear models, random effect of section within herd allowed each herd to differ from one or more of the common parameters of α, β, and γ. Again, compound symmetry correlation structure was included to handle correlation among pigs from the same pen. Other factors could be included for one or more of the parameters and e.g., allow curves to be different for each sex. There were some challenges in estimating random effects for the Gompertz and asymptotic growth variants. One reason could be that the asymptotes were not well covered by data. However, omitting random effect for the γ parameter helped the estimation of random effects for the α and β parameters and was therefore chosen.

Prediction performance of the models was examined in the validation herd ($i = 1$) by the root mean squared error (**RMSE**), a coefficient of determination (**R**^{2}), and the mean absolute error (**MAE**) as defined in the equations below. In these equations, N_1 was the sample size from the validation herd, H indicated the predicted value, H the observed value, and H indicated the average of the observed values.

$$RMSE = \sqrt{\frac{1}{N_1}\sum_{j=1}^{J_1}\sum_{k=1}^{K_{1j}}\sum_{l=1}^{L_{1jk}}\left(H_{1jkl} - H_{1jkl}\right)^2} \quad (7)$$

$$R^2 = 1 - \sum_{j=1}^{J_1}\sum_{k=1}^{K_{1j}}\sum_{l=1}^{L_{1jk}}\left(H_{1jkl} - H_{1jkl}\right)^2 / \sum_{j=1}^{J_1}\sum_{k=1}^{K_{1j}}\sum_{l=1}^{L_{1jk}}\left(H_{1jkl} - H_{1jkl}\right)^2 \quad (8)$$

$$MAE = \frac{1}{N_1}\sum_{j=1}^{J_1}\sum_{k=1}^{K_{1j}}\sum_{l=1}^{L_{1jk}}\left|H_{1jkl} - H_{1jkl}\right| \quad (9)$$

Statistical analyzes were carried out using the statistical software R 4.1.2 (R Core Team, 2021) with a significance level of 0.05. The linear and nonlinear mixed effects models were estimated with the *lme* and *nlme* functions, respectively, from the *nlme* package v. 3.1-153. Decisions on the final order of the polynomial (Q_{final}) and inclusion of other fixed effects were based on χ^2 likelihood ratio tests. As an extra check, prediction performance in the validation herd was calculated also for the polynomial models of order $Q_{final} - 1$ and $Q_{final} + 1$, including other variables from the final model.

In addition to comparing these three types of models, we also compared with two prediction equations from the literature: 1) the second-order polynomial developed by Vorup and Barton-Gade (1991) on basis of 87 growing and finishing pigs (25 to 160 kg) and 21 sows (130 to 260 kg):

$$f_{V1991}(W) = 38.8639 + 0.4272W - 0.000838W^2 \quad (10)$$

and 2) the power function obtained by Condotta et al. (2018) on basis of 150 growing-finishing pigs at five approximate ages with 30 pigs for each age (4, 8, 12, 16, and 20 weeks old):

$$f_{C2018}(W) = 14.4W^{0.35} \quad (11)$$

Results and Discussion

In total 1,435 pigs (148 to 169 from each herd from 288 pens in total) were available for modeling; 673 castrates (47%) and 762 females (53%). In each of 276 pens (96%) five pigs were selected for data collection, in six pens only four pigs were selected, three pens had six pigs, two had three pigs, and one had seven pigs selected. The unequal number of pigs in certain pens is due to counting errors and in a few cases because most pigs from a pen were too large to fit under the plexiglass plate. From the validation herd, data from 179 pigs in 32 pens were available; 97 castrates (54%) and 82 females (46%). In this herd, a larger proportion of pens had data from six pigs (4four pens) or seven pigs (10 pens), while five pens only included four pigs.

Summary statistics on weight and height are shown in Table 2 and a scatter plot can be seen in Figure 2. Six of the pigs from the validation herd weighed from 41.0 to 46.0 kg and were treated separately as these weights are above the range in the training data (2.8 to 40.6 kg). One pig from the training data weighed >40 kg and was kept. The height

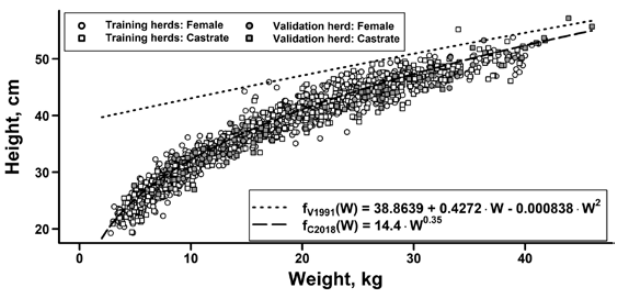

Figure 2. Scatter plot of height and weight. Scatter plot of height (cm) and weight (kg) data from 1,614 nursery pigs from 9 herds used for determining prediction equations (training herds; N = 1,435) and 1 herd used for validation of the prediction equations (grey color; N = 179). The sex is indicated by circles (females) and squares (castrated males). The dotted curve is the prediction from Vorup and Barton-Gade (1991), also shown in Eq. 10. The dash-dotted curve is the prediction from Condotta et al. (2018), also shown in Eq. 11.

predicted from weight by Eq. 10 (obtained from Vorup and Barton-Gade (1991)) and also shown in Figure 2, generally markedly overestimated the height. In contrast, the prediction from Condotta et al. (2018) reproduced in Eq. 11 seems to fit well (Figure 2).

Using herds 2 to 10 (training data) for estimation of polynomial models (Eq. 1), we found a polynomial model of order 3 to be optimal. In this, a sex-dependent intercept was significant ($\chi^2_1 = 8.23,\ P = 0.004$), whereas interactions between sex and the other parameters of the polynomial were not statistically significant. None of the herd characteristics were significant. Though a significant change of intercept was found with female pigs being 0.25 cm taller than castrates (at the imaginary weight of 0 kg), this seems modest from the larger perspective. Therefore, prediction equations with common intercept (leaving sex out of the model) were also determined. The parameter estimates for second, third, and fourth order polynomials with and without inclusion of sex are shown in Table 3, and the corresponding prediction curves with sex-specific intercept are shown in Figure 3.

The power function (Eq. 3), obtained by estimating a linear mixed effects regression (Eq. 1) of log(height) against log(-weight), also had a significant effect of sex on the log-scale intercept ($\chi^2_1 = 9.11,\ P = 0.003$). Parameters for the prediction equations with and without this sex dependency are given in Table 3, and sex-specific curves are presented in Figure 3.

For the nonlinear growth models (see Eqs. 4 to 6), all three parameters had significant dependency on sex; both when testing all simultaneously ($\chi^2_3 \in \{10.6, 10.6, 11.6\},\ p \in \{0.014, 0.014, 0.009\}$ for the asymptotic, Gompertz, and logistic growth models, respectively), and when testing each parameter separately (results not shown). Nevertheless, as for the polynomial models we estimated models with and without sex-specific parameters. Estimates are shown in Table 3, and corresponding prediction curves for the models including sex are given in Figure 3.

The performance of predicting height from weight in the validation herd (herd 1) with the different models is shown in Table 4. Calculations are shown for the 173 pigs weighing ≤ 40 kg and separately for the six pigs weighing > 40 kg. The negative coefficient of determination in this latter group essentially means that the fit is worse than a horizontal line, i.e., that the models do not fit well for these pigs outside the weight interval for which the models were fitted. Among the polynomial models, orders three and four fit equally well for the 173 pigs, whereas the third-order polynomial manages a bit better than the one of order four, for the six largest pigs. This finding works both with and without the inclusion of sex in the models, but as expected (since it is significant), models including sex-specific intercept performed better than those without, though differences are small. The performance of the power function was equivalent to the polynomial of order three, slightly better though for the six largest pigs. Among the nonlinear growth models, the asymptotic model had a slightly better performance than Gompertz, followed by the logistic model. The former two performed in between the second and third/fourth-order polynomial models. The logistic model performed a bit worse than the second-order polynomial model. None of them had a good fit for the largest six pigs.

Table 3. Parameter estimates for prediction models to determine the heights of nursery pigs at different weights. Castrated males (Cast.); females (Fem.); sex-specific parameters (+Sex); common parameters across sex (–Sex)

Model	Parameter estimates						
Polynomial	β_0		β_1		β_2	β_3	β_4
+ Sex	Cast.	Fem.					
2nd order	17.9	18.2	1.50		−0.0183	–	–
3rd order	15.4	15.7	2.05		– 0.0495	0.000506	–
4th order	14.9	15.1	2.23		– 0.0656	0.00107	– 6.77e-6
– Sex							
2nd order	18.0		1.51		– 0.0185	–	-
3rd order	15.5		2.06		– 0.0500	0.000514	–
4th order	15.0		2.21		– 0.0635	0.000990	– 5.68e-6
Power function	A		B				
+ Sex	Cast.	Fem.					
	13.9	14.0	0.354				
– Sex	14.0		0.353				
Nonlinear	A		B		γ		
+ Sex	Cast.	Fem.	Cast.	Fem.	Cast.	Fem.	
Asymptotic	54.3	53.5	15.8	15.3	– 2.95	– 2.88	
Gompertz	1.07	1.08	51.8	51.3	0.928	0.924	
Logistic	50.5	50.0	5.22	5.02	10.2	9.56	
– Sex							
Asymptotic	53.8		15.5		– 2.91		
Gompertz	1.08		51.4		0.925		
Logistic	50.1		5.07		9.78		

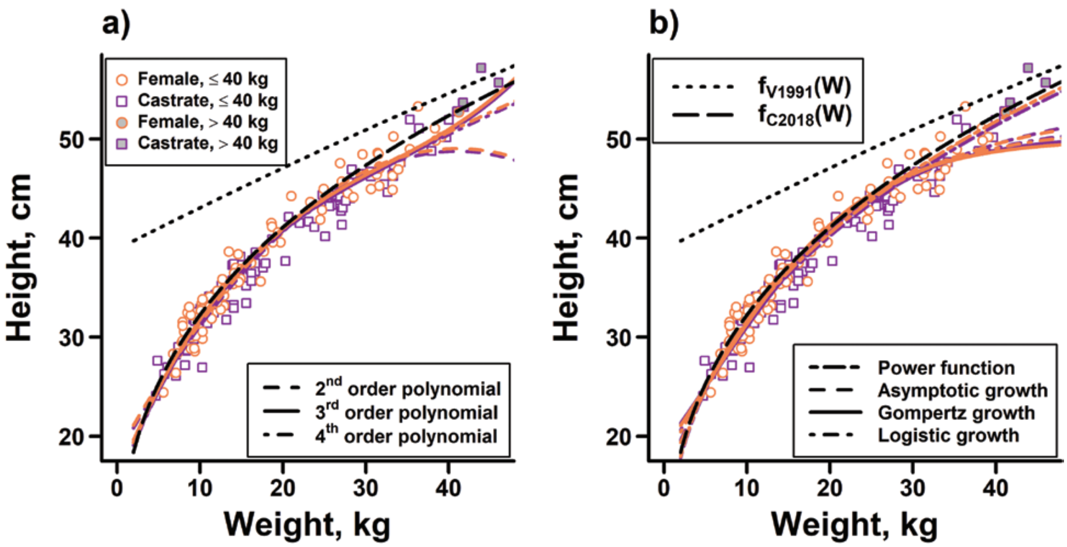

Figure 3. Scatter plot of 179 nursery pigs' height vs. weight from the validation herd. Scatter plot of 179 nursery pigs' height (cm) vs. weight (kg) from the validation herd. Sex-specific prediction curves for (a) polynomial models and (b) power function and non-linear growth models. The dotted curve in each panel is the prediction from Vorup and Barton-Gade (1991), also shown in Eq. 10. The long-dashed curve is the prediction from Condotta et al. (2018), also shown in Eq. 11.

Table 4. Performance of models with sex-specific (+ Sex) or common parameters (– Sex) for prediction of height from weight for 179 nursery pigs from a validation herd (herd no. 1), divided into pigs weighing ≤ 40 kg and > 40 kg, respectively. The measures shown are the root mean squared error (RMSE, Eq. 7), a coefficient of determination (R^2, Eq. 8), and the mean absolute error (MAE, Eq. 9)

Model	Pig weight ≤ 40 kg (N = 173)			Pig weight > 40 kg (N = 6)		
Polynomial	RMSE	R^2	MAE	RMSE	R^2	MAE
2nd order + Sex	1.62	0.947	1.31	5.81	−11.3	5.52
3rd order + Sex	1.56	0.951	1.25	2.21	−0.785	1.95
4th order + Sex	1.56	0.951	1.25	2.93	−2.13	2.68
2nd order – Sex	1.66	0.945	1.33	5.77	−11.2	5.49
3rd order – Sex	1.59	0.949	1.26	2.13	−0.648	1.87
4th order – Sex	1.59	0.949	1.26	2.72	−1.69	2.48
Power function						
+ Sex	1.54	0.953	1.25	2.00	−0.461	1.62
– Sex	1.57	0.951	1.27	1.85	−0.252	1.48
Nonlinear growth						
Asymptotic + Sex	1.59	0.949	1.27	4.37	−5.96	4.15
Gompertz + Sex	1.61	0.948	1.29	4.90	−7.77	4.69
Logistic + Sex	1.65	0.945	1.33	5.26	−9.09	5.05
Asymptotic – Sex	1.63	0.947	1.29	4.42	−6.13	4.20
Gompertz – Sex	1.66	0.945	1.32	4.98	−8.03	4.76
Logistic – Sex	1.70	0.942	1.36	5.42	−9.71	5.20
Model from 1991[1]						
2nd order – Sex	9.10	− 0.661	8.38	1.78	−0.158	1.71
Model from 2018[2]						
Power function – Sex	1.81	0.934	1.46	1.31	0.377	0.770

[1]Vorup and Barton-Gade (1991).
[2]Condotta et al. (2018).

The coefficient of determination for pigs weighing ≤40 kg was 0.95 for all models except for the logistic without sex, for which it was 0.94. Vorup and Barton-Gade (1991) had equivalently an R^2 of 0.95 for the prediction equation shown in their Figure 1 and reproduced here in Eq. 10, though we do not know for sure if the authors applied the same formula for the coefficient of determination. It is worth noting that among the 10 lightest pigs in their study, 9 had a height below the prediction curve. As evident from Figure 2, except for a handful, all pigs in the current study had a height below this curve. Correspondingly, the performance measures indicate that fitting these heights from the weights with Eq. 10

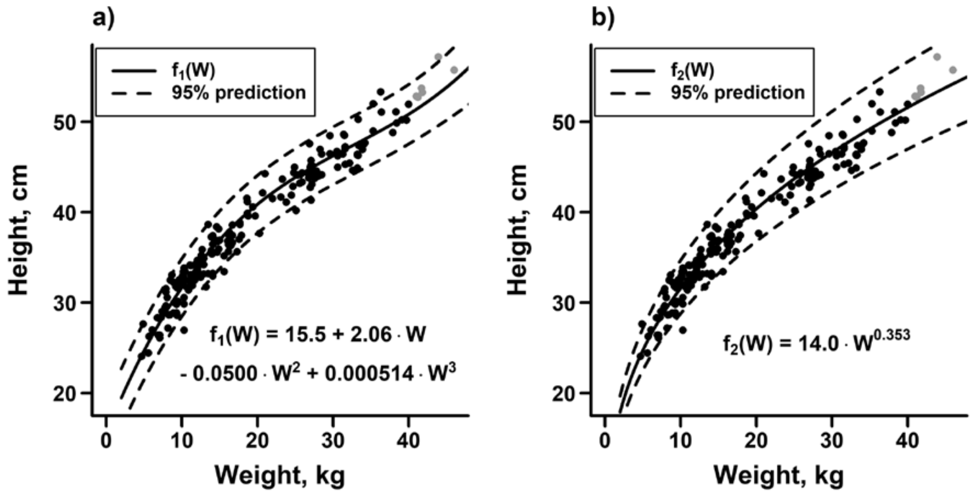

Figure 4. Scatter plot of height vs. weight of 179 nursery pigs from the validation herd. Scatter plot of height (cm) vs. weight (kg) of 179 nursery pigs from the validation herd. Prediction curves using (a) a third-order polynomial without sex-specific intercept (Eq. 12) and (b) a power function (Eq. 13). Moreover, 95% prediction curves (dashed lines).

results in a poor fit. An exception is perhaps the six heaviest pigs for which the performance was better than by using the equations put forward in the present study, though the R^2 was still negative. Predicting the height of the pigs from the nine herds included in the present training data by Eq. 10 results in an RMSE of 10.4, an R^2 of −0.60, and a MAE of 9.30. Breaking these into five kg bins, i.e., (0,5], (5,10],..., (35,40.6], the RMSE decreases from 17.3 for those in the (0,5] kg interval to 4.5 for those the (35,40.6] kg interval. Correspondingly, R^2 increased from −107.1 to −5.1 and MAE decreased from 17.3 to 4.1. That is, the prediction went from bad to worse as the weight decreased.

In contrast to this, the prediction equation for height from weight determined by Condotta et al. (2018), and reproduced in Eq. 11, performed almost as well for the validation herd as the equations found in the present study for the pigs until 40 kg, and even better for the 6 heaviest, being the only equation managing to return a positive coefficient of determination for this small subgroup (Table 4).

Overall, the two best prediction models, among those presented here, were the power function with sex-specific log-intercept and the third-order polynomial with sex-specific intercept. Nevertheless, since the prediction, for practical considerations, only differs marginally between females and castrates, we suggest to use the models with common intercepts for prediction of height from weight. Thus, we recommend either the following third-order polynomial

$$f_1(W) = 15.5 + 2.06W - 0.0500W^2 + 0.000514W^3 \quad (12)$$

or the following power function

$$f_2(W) = 14.0W^{0.353} \quad (13)$$

both of which are shown in Figure 4 with 95% prediction curves. These functions are valid for weights between 5 and 40 kg and should not be used outside this range, though they will probably fit reasonably well down to 3 kg. The coefficients for the other models are shown in Table 3, enabling the use of these, if preferred. It is worth noting that the power functions given by Eq. 11 (determined by Condotta et al., 2018) and Eq. 13 are quite similar though heights predicted by Eq. 11 are slightly, but systematically, higher as also visible in Figure 3.

The aim of the present study was to determine the height of pigs from 5 to 40 kg of body weight. Since, in Danish private herds, the day of weaning can often not be determined after pigs are moved to the nursery pens (due to for example inter-litter mixing and no individual marking of pigs), we decided not to include days since weaning as a parameter in the prediction and thus to let all pigs found in nursery pens potentially be part of our sample. Measures were taken to avoid pigs above 40 kg though one pig of 40.6 kg slipped into the training data, whereas pigs weighing less than 5 kg were kept to get a better fit of the curve near 5 kg. It could be argued that pigs in the early days after weaning may not gain weight, or even lose weight, which would affect the weight:height-ratio, but since the weaning date usually will be unknown, it appeared to be a better solution to ignore this and include all pigs found in the nursery pens into our general population from where the experimental pigs were drawn in a random way. From an animal transport perspective, piglets may be relocated early after weaning, but according to European legislation, they have to be at least 10 kg to take part in journeys of over 8 hours (European Regulation, 1/2005), and according to Dahl-Pedersen and Herskin (2021), the majority of pigs transported for further fattening in the EU weigh approximately 30 kg. This means that the presented predictions of the relation between height and weight cover the most relevant weight categories.

Figure 4 shows the predicted height of pigs in the weight interval from 5 to 40 kg as well as the 95% prediction curves. According to the current EU Regulation (EC, 1/2005), the height provided in means of transport should be appropriate to the size of the animals and the intended journey. In addition, it is stated that adequate ventilation, when animals are in a naturally standing position, should be offered without on any account hindering the natural movements of the animals. Specific deck height requirements are not given for pigs, but EFSA (2002) recommended a deck height of at least 15 cm above the pigs in mechanically ventilated trucks, and at least 30 cm when only passive ventilation is possible. Most trucks transporting pigs in the weight interval from 10 to 40 kg can accommodate five or four decks, leading to a deck height of approximately 60 to 70 cm, respectively. Based on the current results of the third-order polynomial, for example, the predicted height of an average 30 kg pig would be 46.2 cm, and the upper 95% prediction curve would be at 49.4 cm, which means that the average pig of 30 kg, which is the typical size of pigs transported for further fattening in Europe, would have 13.8 cm, and at the upper 95% prediction limit the pigs would have at least 10.6 cm of headroom if a deck height of 60 cm was used, and 10 cm more if 70 cm was used. Recently, the EFSA AHAW Panel (2022) called for further research to establish evidence-based thresholds for deck height. The current results may form the basis of such work. Concerning animal welfare, it is important, though, to state that a given deck height should not only fit the average pig, but in principle fit the tallest pig in a load. The 95% prediction curves can be used to give information about the variation and could be taken into consideration if thresholds for deck height are formulated.

Conclusion

The present results have determined height of pigs of approximately 5 to 40 kg. Based on the development of prediction models, it is proposed to use either a third-order polynomial (Eq. 12) or a power function (Eq. 13) to predict height based on body weight of nursery pigs, at least originating from the DB or the DG breeding systems. The functions were validated for nursery pigs between 5 and 40 kg, but are expected to remain valid down to 3 kg. Information about body weight of pigs is often known, whereas height is more difficult to determine, but relevant for the development of pig housing and especially pig transportation.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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