EVALUATION OF THE ACCURACY OF SIMPLE BODY MEASUREMENTS FOR LIVE WEIGHT PREDICTION IN GROWING-FINISHING PIGS

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Animal Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2009

Urbana, Illinois

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ABSTRACT

Two studies were carried out to evaluate the accuracy of simple body measurements to predict the live weight of growing-finishing pigs. Study I used 72 barrows from a Landrace-based line; Study II used 72 barrows from each of a Landrace-based (the same line as used in Study I) and a Duroc-based line. Study I was carried out between 57.5 ± 7.1 and 126.6 ± 7.45 kg BW; Study II between 40.6 ± 4.9 and 126 ± 8.4 kg BW. In both studies, pigs were weighed every 2 wk and various body dimensions were taken on the live animal and on dorsal- and lateral-view photographic images of the pig taken at the time of weighing. Stepwise regression analysis was used to develop equations to predict live weight from body measurements. The highest R^2 values were obtained for regression equations based on live animal measurements such as chest circumference [R^2= 0.95; Residual Standard Deviation (RSD) = 5.7 kg], and flank circumference (R^2= 0.94; RSD = 6.5 kg). Regression equations based on live-animal measurements generally gave higher R^2 values than those based on measurements on the photographic images; e.g., in Study I the equation based on shoulder height gave R^2 of 0.84 (RSD = 10.5 kg) for the measurement taken on the live animal compared to R^2 of 0.26 (RSD = 18.2 kg) for the same measurement taken on the lateral image. Combining measurements to calculate body surface areas or volumes gave little improvement in R^2 when those for the respective individual measurements were already high. Estimates of weighing period, and genotype biases for weight prediction were small, although, significant ($P > 0.05$) for the prediction equations from both studies. The results of this study suggest that regression equations based on simple body measurements can be used to accurately predict live weight of growing-finishing pigs.

To my Parents and Siblings

ACKNOWLEDGMENTS

I would like to offer my most sincere appreciation to my advisor Dr. Michael Ellis for his guidance, encouragement, and friendship shown to me during this phase of my education. I would also like to thank the remaining members of my committee, Drs Floyd McKeith, John Killefer, Jan Novakofski, and Beau Peterson for their advice and support.

To my fellow graduate students, past and present, Alvaro Rojo, Caleb Schull, Chad Pilcher, Chris Puls, Hanna Rothe, Jose Charal, Omarh Mendoza, Marleny Mercedes, Tina Peterson, and lab member Janelle Schilpf I would like to extend my sincere gratitude for their friendship, assistance and support, especially on those good and long days at the farm.

Finally, I owe a great debt of gratitude to my family, who, regardless the distance always showed their love to me. My parents were always my best example and my inspiration to cope with the sacrifices needed for great achievement

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CHAPTER I

INTRODUCTION

Pork processing plants have established strict standards in terms of the weight of the pigs they receive and process in order to obtain a final product that meets the cut sizes preferred by consumers. Failing to meet the standards of processing plants often results in penalization on the price producers receive for the animals, therefore, from an economic standpoint, it is critical to send pigs to market within the weight range required by the plant. Traditionally in the US, the selection of animals has been carried out manually by the farm crew, walking through the pens and selecting the biggest animals on the basis of visual appraisal. However, there is variation between individuals in their ability to predict the live weight of pigs from visual appraisal, which will increase the variation in the weight of the animals that are sent to market (Schofield et al., 1990). Although this variation in weight of pigs selected for market could be reduced by manually weighing the animals using a weigh scale, authors such as Brandl and Jørgensen (1996), White et al. (2004), and Wang et al. (2008) agreed that the use of weighing scales under commercial conditions is problematic and is limited by a number of factors including the time involved, the increased labor needed, the stress on the pigs and the people involved, and the lack of availability of weigh scales on the unit. As an alternative, a number of semi-automatic or automatic weighing scales have been developed to be placed inside of the pens. However, this equipment tends to ultimately to fail and become inaccurate because of the constant physical contact of the machine with the animal and the dirty environment (White et al., 2004). Therefore, an accurate method to measure the weight of the animals without the problems involved in the use of mechanical scales will have a potential value from both the production and research standpoints. In the search of such prediction method, a number of technologies have been developed to predict the live weight on animals of several species, including the use of linear body measurements in cattle and sows, and photograph analysis in finishing pigs. However, the accuracy of prediction of weight varies between different methods, and not all of them are suitable to be used under commercial situations. The ideal system to predict live weight in pigs would not only accurately predict the live weight of the animal, but should also avoid the problems related with the use of scales outlined above. Therefore, the objective of the current study was to investigate the accuracy of a range of simple body measurements taken either directly on the animal or on photographic images, to predict the live weight of growing-finishing pigs.

CHAPTER II

REVIEW OF LITERATURE

Importance of Live Weight in Livestock Enterprises

There are many reasons to consider the weighing of the animals as one of the most important tasks to perform when managing livestock. Authors such as Schofield et al. (1990 and 1999), Brandl and Jørgensen (1996), Enevoldsen and Kristensen (1997), Frost (1997), Sarti et al. (2003), Wu et al. (2004), Robinson (2005), Dingwell et al. (2006), and Wang et al. (2006 and 2008) support this idea and agree that such activity brings benefits to producers from a number of standpoints.

First, as an indicator of animal health and growth, providing valuable information regarding the nutritional and environmental conditions on the farm. Secondly, it helps to determine the time when the animals are ready to be sent to market. Additionally, it is important for the understanding of factors that can affect the output of the herd, such as space allowance (Brandl et al., 1996). Furthermore, live weight is an essential tool in the determination of growth rate and food conversion efficiency which, according to Schofield et al. (1990 and 1999), are highly significant parameters in the control of production costs to maintain profits on commercial pig operations. In general, feed cost represents around 60% of the total production costs, and because of that, maintaining the optimum growth rate and food conversion efficiency is key to low-cost production. However, growth rate and food conversion efficiency are affected by several factors (e.g., diet formulation and ingredients, genetic potential, environmental conditions, etc.) and unless live weight is measured regularly and accurately, the pig producer will not be able to assess the effect that any change in husbandry, feed quality, or environment have on the animals (Schofield et al., 1990; Brandl et al., 1996; Schofield, 1999; Sarti et al., 2003; Wang et al., 2006).

Another example can be seen in the cattle industry, where knowledge of live weight can be used in the development of nutritional management programs for replacement heifers (Donovan and Braun, 1987), the evaluation of feed efficiency, the determination of pharmaceutical doses of drugs, and in the appraisal of the overall health status of the animals (Enevoldsen and Kristensen, 1997). In addition, live weight information can be used to help producers in achieving goals for age at first calving and to determine the value of culled animals and the efficiency of rearing replacement heifers (Dingwell et al., 2006).

Also, changes in composition in pigs were reported to be related with live weight (Shields et al., 1983). In that study, it was shown that carcass weight increased linearly with live weight, while other body component such as the percentages of fat and protein increased quadratically with live weight. This raises the possibility of estimating changes in carcass weight and composition based on *in-vivo* measurement of live weight.

Therefore, for all the valuable information that measurement of weight and weight gain can bring, they are two of the most frequently analyzed traits in farm livestock. However, the optimal use of both in all species will depend on the accuracy of measurement of live weight and sources of potential bias in any measurement (Robinson, 2005).

Weight Prediction in the Swine Industry

In general, there are two ways to measure the weight of the animals; direct weighing, involving the use of a weigh scale, and indirect weighing, where no weigh scale is used (Wang et al., 2006). For a typical direct weight measurement, the animals have to be manually moved to a weighing location and placed on a weigh scale. This requires a high input of labor, results in changes in the feeding behavior of animals (Augspurger and Ellis, 2002), and can stress animals to the point of weight loss, health deterioration, and, in the extreme, even death of the animal (Wang et al., 2006, Schofield, 1990). For that reason, only a small number of producers perform direct weight measurements. Instead, most farmers estimate the weight of the animals by direct visual appraisal. However, the farm profits will depend on the skills of the workers to identify animals within the relatively narrow weight range required to obtain premium grade and price at the slaughter plant (Wang et al., 2006; Schofield, 1990).

Another problem associated with direct methods for weighing pigs is the error of the weight measurements. The sources of errors are commonly related with mistakes in the calibration and reading of the scales, but it can also be due to short-term factors that result in variation in the live weight of the animal such as water retention and gut fill. This variation can be more relevant when weight change is used to calculate the increase in true body mass over a specific period of time, particularly over relatively short time periods, since it is known that both water retention and gut fill change during the course of the day (Robinson, 2005).

For those reasons, implementation of accurate indirect methods for weight measurements has a great potential for overcoming the problems related with direct weighing methods in swine production (Yeo and Smith, 1997).

Linear Measurements in Weight Prediction

The relationships between body size and shape of the animals, and different production traits, such as live weight, growth rate, carcass weight, milk yield, and nutritional requirements, have been investigated in different species by several authors (Shields et al., 1983; Heinrichs et al., 1992; Wilson et al., 1997). These relationships are considered an important way to describe growth and development of animals, and authors such as Hammond (1955) attributed the same relevance to linear and volume measurements as to measurements of mass (Whittemore and Schofield, 2000).

The origin of the study of body size and shape goes back to the year 1837 when Sarrus and Rameaux formulated the "Surface law", which addressed the relationship between heat production and linear size and surface area of animals. Later, Brody (1945) applied the principles of the surface law to estimate live weight of animals from their surface area, and showed that surface area varies with the 2/3 power of weight ($S = \alpha W^{2/3}$; where S = surface area, α = constant, W= weight).

According to Whittemore and Schofield (2000), the emphasis given by Brody to the relationship between surface area and live weight was due to the high correlation existing between these two measurements; making surface area a potentially accurate indicator of growth. Whittemore and Schofield (2000) also presented an important discussion to justify the implementation of size and shape scaling in the determination of nutrient requirements of breeding sows by sugesting live weight as an irrelevant and sometimes deceptive measurement by itself; instead, he gave more relevance to the sow size and shape, as an indicator of the animal's uterine and gut capacity, mammary volume, and body condition.

Heinrichs et al. (1992) carried out a study with cattle using data from 2,625 observations and regressed live weight against various body measurements such as the height to the withers, heart girth, wither height, hip width, or body length. The authors concluded that each measurement could be used for predicting live weight due to the high strength of association (R^2>0.95). In addition, they showed that from all measurements regressed with live weight, heart girth (measured as the circumference of the animal immediately behind the front legs and in front of the first mammary gland) had the greatest correlation with live weight followed by hip width. As a matter of fact, among all measurements, heart girth has been the most commonly used in practice to predict live weight (Dingwell et al., 2006).

Image-based Live Weight Prediction

Despite the potential that linear measurements have for describing the growth of the animals and other productive traits (e.g. carcass morphology and composition), most of these measurements still involve direct contact between the animal and the operator, therefore, limiting their practical use (Wang et al., 2008). For example, the use of direct measurements of heart girth in pigs has been limited almost exclusively to those animals housed under certain restriction of movement such as sows housed in gestation crates (Yeo and Smith, 1997). However, the use of different image analysis systems has made possible the study of correlations between body dimension and other production traits in a non-invasive way. Several studies have been carried out with different species, and evaluating different systems of image analysis to predict the production traits of interest. In the area of dairy research, Bewley et al. (2008) investigated the use of digital image analysis to estimate body condition scores in dairy cattle by manually identifying several anatomical points of the animal from the images; the highest correlation between measurements from the images and body condition scores had a R^2 of 0.52.

The prediction of carcass composition and meat quality using image analysis has also been evaluated. Lambe et al. (2008) used different measurements on live animals, including video image analysis, ultrasound, and X-ray computer tomography, among others, to determine the best method or methods for prediction of carcass and meat quality traits in Texel and Scottish Blackface lambs. However, in that study the use of the video image analysis was limited due to the need to shear the lambs before measurement, therefore, limiting the possibilities of practical use in the industry, since most of animals are not shorn in practice (Lambe et al., 2008). Meanwhile, in the swine research area, McClure et al. (2003) evaluated the accuracy of a video image analysis system to predict carcass meat yield in pigs, employing the video recording system VCS2001, E+V (Oranienburg, Germany). The system captured video images from pork carcasses in a packing plant, in order to predict the yield of prime cuts from those carcasses. The accuracy in prediction obtained by the system among different cuts ranged from $R^2 = 0.88$ for total saleable product weight, to $R^2 = 0.55$ for the weight of the spareribs, showing that the image-based system performed with accuracy similar to other methods currently available, such as Fat-O-Meater, in predicting the weight of total saleable product and fat-corrected lean.

Using a different approach to estimate carcass morphology and composition based on image analysis, Doeschl et al. (2004) used the visual image analysis system (VIA) described by Schofield (1990) to record images of live animals in a daily basis, and based its estimations on linear and areal measurements of the top (dorsal) plane of the animal. Doeschl et al. (2004) concluded that a significant relationship existed between body measurements taken by the VIA system on the animals immediately before slaughter, and the composition of the carcasses, with R^2 values for carcass fat weight (relative to the dissected carcass side weight) ranging from 0.41 to 0.70. The author also suggested a possible relevance of the shape of the trunk to describe fat and lipid weight, while the regions of shoulders and ham appeared to be better descriptors of relative muscle and protein content (Doeschl et al., 2004)

In addition to using image analysis to predict carcass composition and morphology, image analysis systems have also been studied to predict and describe the live weight growth of different species. One of the most widely studied images systems for live weight prediction is the previously described VIA system. An early version of this system was used to predict live weight and body composition of the pigs by Schofield (1999); Negretti et al. (2008) used an updated version of the system on Mediterranean buffalo. Schofield et al. (1999) concluded that the system could use the data from individual observations to estimate the mean weight of the group of pigs under study with a confidence interval of ±5%, while Negretti et al. (2008) reported a R^2 of 0.96 for the equation for live weight prediction using the surface area of the lateral profile of the buffalo and of the hindquarters. A different method was used by Wang et al. (2006 and 2008) for image analysis, measuring the width of the shoulders, center, flank, torso and hip of the animal, and calculating different surface areas of the animal based on the width measurements. The highest correlation ($R^2 = 0.97$) with live weight was with the top view area of the pig (excluding the head); the weight of a 75kg pig was predicted within a confidence interval of ±6.2%, confirming that live weight can be accurately estimated using image-based (Wang et al., 2006).

In addition, Yan and Guanghui (2008) presented a method for live weight estimation based on the technique of measuring the projected areas and height of the animals (Schofield et al., 1999), however, in this case, they used cameras on the top of the ceiling and side of the wall, in order to record images of the dorsal and lateral views of the pigs. The method employed utilized projected areas from the image of the pigs captured directly from top view, and then the height was obtained using the side view images. Estimating the weight of the animal using both the area and the height measurements resulted in a mean relative error of the predicted weight of 3.2% when compared with the real weight (Yan and Guanghui, 2008).

These previous studies show the potential of image analysis technologies for the accurate prediction of live weight, and, therefore, open up the possibility to use this approach under practical condition in livestock industries as a useful tool to monitor growth of animals, with all the advantages previously described that this implies.

CHAPTER III

MATERIALS AND METHODS

The studies reported in this thesis were conducted at the University of Illinois Isolation Facility. Experimental protocols were approved by the University of Illinois Institutional Animal Care and Use Committee.

Experimental Design

The study used a regression-based approach to establish the most appropriate equations to predict live weight from simple body measurements and image analysis.

Animals

The experiment used pigs that were involved in two different studies. Study I used 72 barrows from a line based on the Landrace breed that had been classified into three birth weight categories, namely 24 light birth weight pigs (0.9 kg ± 0.3 kg), 24 medium birth weight pigs (1.6 kg ± 0.3 kg), and 24 heavy birth weight pigs (2.3 kg ± 0.3 kg). The measurements of the animals started when the pigs averaged 57.5 (± 7.1) kg live weight and ended when the pigs averaged 126.6 (± 7.45) kg live weight. Study II used 144 barrows from two lines namely a Landrace-based (the same line used in Study I) and a Duroc-based line, also classified into three birth weight categories with 24 light birth weight pigs (0.9 kg ± 0.3 kg), 24 medium birth weight pigs (1.6 kg ± 0.3 kg), and 24 heavy birth weight pigs (2.3 kg ± 0.3 kg) for each genetic line. The measurement of the animals started when the pigs averaged 40.6 (± 4.9) kg ended when the pigs averaged 126.6 (± 8.47) kg.

Housing

Study I: The animals were housed in two rooms of the same building and kept in individual pens. The flooring was of plastic slats, and pen divisions and gates consisted of vertical steel rods. Pen dimensions (length x width) measured 2 x 1 m, providing a floor space of 1.9 m^2/pig (pen floor area minus the space taken by the feeder). Each pen had a single-space dry box-type feeder, and one Drink-O-Mat cup drinker.

Study II: Animals were housed in four rooms of the same building and kept in pens of 9 pigs. The flooring was of concrete slats, and pen divisions and gates consisted of vertical steel rods. Pen dimensions (length x width) measured 3.7 x 1.8 m, for a total pen area of 6.4m^2, providing a floor space of 0.74 m^2/pig (pen floor area minus the space taken by the feeder). One two-hole Farmweld dry feeder, and one Drink-O-Mat cup drinker were available in each pen.

For both studies, the thermostat was set at 21^{o}C throughout the study period and maintained using heaters and fan ventilation. Temperature and humidity were recorded with HOBO H8 data loggers that were set to record every 12 minutes.

Diets

Study I. The objective of this study was to evaluate the impact of feeding Paylean to pigs of different birth weights (i.e., light, medium, and heavy). From 3 weeks post-weaning to 109 kg BW, pigs were fed a 5-phase dietary program. Diets were based on corn and soybean meal and were formulated to meet or exceed NRC (1998) recommendations for the nutrient requirements of pigs of the weight used. At 109 kg BW, pigs started the Paylean phase of the study with half of the pigs being fed a diet without Paylean and the other half receiving a diet with Paylean included at 5ppm. During the Paylean phase of the study, diets were formulated to meet the requirements of the pigs receiving Paylean. Pigs had ad libitum access to feed and water throughout the study period. Diet phases were changed on the basis of pig body weight.

Study II. The study was designed to evaluate the effect of number of dietary phases on growth performance and had four dietary treatments: 1) Standard four-phase feeding program (control) with no antibiotic, 2) Single-phase program with no antibiotic, 3) Control diet with 10g/ton of *virginiamycin*, 4) Control diet with 10g/ton of *tylosin*. In addition, the effect of birth weight (light, medium, and heavy) on growth performance was evaluated. Diets were based on corn and soybean meal and were formulated to meet or exceed NRC (1998) recommendations for the nutrient requirements of pigs of the weight used (40.0 kg to 118.0 kg BW), with the exception that the single-phase treatment was formulated to protein and lysine levels that were at the requirement of pigs of the midpoint of the weight range evaluated (75 kg). Pigs had ad libitum access to feed and water throughout the study period. Diet phases were changed on the basis of average pen live weight.

Growth Performance Evaluation

Live weight measurements and feed consumption. During both studies all pigs were individually weighed every two weeks. All feed additions and feed remaining in the feeder at the time of pig weighing were measured to determine feed intake and gain:feed ratio.

Body measurements. Body measurements were taken using two different approaches, either directly on the live animal, or on dorsal and lateral photographs of the animal. Live animals measurements and photographs were taken on the animal at the same time that the pigs were weighed. Before each photograph was taken, a 10cm aluminum ruler was used as a dimensional reference and was placed on the back or the ribs of the animal for the dorsal and lateral photographs, respectively. The analysis of photographs was carried out as follows: the number of pixels contained in the body dimensions and the aluminum ruler were measured on each photograph using the computer program Digital Image Basics (2008, Museum of Science, Boston, MA) and a pixel:cm ratio was calculated for each photograph by measuring the numbers of pixels contained in the ruler. This pixel:cm ratio was used to transform all the measurements taken on the photographs of the animals into cm.

The various measurements taken on the live animal and the photographs are summarized in Table 1.

i. *Direct measurements taken on the live animal and/or the photographs:*

a. Shoulders height (cm): Measured from the top of the shoulder from the mid-point of the shoulder blade of the animal to the floor in a perpendicular line. For measurements on the live animal, an adjustable ruler was used, placing it perpendicular to the floor with the movable arm resting on the shoulder of the animal (Figure 1).

b. Body length (cm): Measured along the back on the midline, from the base of the tail to the middle of the shoulder blade. A measuring tape was used for measurements taken on the live animal (Figure 2).

c. Shoulder width (cm): Measured at the widest point of the shoulder. For measurements on the live animal a caliper was placed on top of the animal, in contact with the outside of both shoulders (Figure 3).

d. Hip width (cm): Measured at the widest point of the hip. For measurements on the live animal a caliper was placed on the top of the animal, in contact with the outside of both hams (Figures 3).

e. Chest circumference (cm): Measured immediately behind the front legs using a measuring tape (Figure 4).

f. Flank circumference (cm): Measured immediately in front the hind legs using a measuring tape (Figure 4).

ii. Additional direct measurements taken on the photographs:

a. Chest width: Measured immediately behind the front legs (Figure 4).

b. Flank width: Measured immediately in front the hind legs (Figure 4).

c. Chest depth: Measured immediately behind the front legs (Figure 4).

d. Flank depth: Measured immediately in front the hind legs (Figure 4).

e. Cross shoulder to hip distance (cm): Measured between the shoulder and the hips by averaging the following measurements:

  i. Left shoulder to right hip distance (cm): Measured from the widest point of the left shoulder to the widest point of the right hip (Figure 5).

  ii. Right shoulder to left hip distance (cm): Measured from the widest point of the right shoulder to the widest point of the left hip (Figure 5).

f. Cross chest to flank distance (cm): Measured between the chest and the flank by averaging the following measurements:

  i. Left chest to right flank distance (cm): Measured from the widest point of the left side of the chest to the widest point of the right side of the flank (Figure 6).

  ii. Right chest to left flank distance (cm): Measured from the widest point of the right side of the chest to the widest point of the left side of flank (Figure 6).

g. Middle back height (cm): Measured from the middle of the back to the floor in a perpendicular line (Figure 7).

h. Base of the tail height (cm): Measured from the base of the tail to the floor in a perpendicular line (Figure 7).

i. Trunk depth (cm): Measured at the middle point of the trunk from the top of the back to the bottom of the belly in a perpendicular line (Figure 7).

iii. *Calculated measurements from direct measurements:* The following body measurements were calculated using various combinations of the direct measurements taken on the live animals or on the photographs previously described.

a. Shoulder cross-sectional area (cm^2): The shoulder width measured on the live animal was used to calculate the diameter of a circle, which was used to estimate the circular area of a cross-section of the body at the shoulders (Figure 8).

b. Shoulder circular dorsal area (cm^2): The shoulder width measured on the dorsal photographs was used to calculate the circular area of the dorsal plane of the body at the shoulders (Figure 9).

c. Hip cross-sectional area (cm^2): The hip width measured on the live animals was used to calculate the diameter of a circle, which was used to estimate the circular area of a cross-section of the body at the hips (Figure 8).

d. Hip circular dorsal area (cm^2): The hip width measured on the dorsal photographs was used to calculate the circular area of the dorsal plane of the body at the hip (Figure 9).

e. Chest cross-sectional area (cm^2): The diameter of a circle was calculated from the circumference of the chest to estimate the circular area of a cross-section of the body at the chest (Figure 8).

f. Chest circular dorsal area (cm^2): The chest width measured on the dorsal photographs was used to calculate the circular area of the dorsal plane of the body at the chest (Figure 9).

g. Flank cross-sectional area (cm^2): The diameter of a circle was calculated from the circumference of the flank to calculate the circular area of a cross-section of the body at the area. (Figure 8).

h. Flank circular dorsal area (cm^2): The flank width measured on the dorsal photographs was used to calculate the circular area of the dorsal plane of the body at the flank (Figure 9).

i. Body area (cm^2): The area of a trapezoid was calculated using the shoulder and hip width, and body length measurements (Figure 10).

j. Chest/flank volume (m^3): The volume of a cylinder was calculated using the body length and the average of the chest cross-sectional area and flank cross-sectional area as the area of the base of the cylinder (Figure 11).

k. Body volume (m^3): The volume of a cylinder was calculated using the body length and the average of hip cross-sectional area and shoulders cross-sectional area as the area of the base of the cylinder (Figure 12).

iv. Additional calculated measurements on photographs:

a. Trunk area (cm^2): The area of a trapezoid was calculated using the chest width, flank width and chest to flank distance (Figure 13).

b. Area 1 (cm^2): The area of a rectangle was calculated by averaging the shoulder height, middle back height and base of tail height measurements, and multiplying by the body length measurement (Figure 14).

c. Area 2 (cm^2): The area of a rectangle was calculated by averaging chest, trunk, and flank depth measurements, and multiplying by the body length measurement (Figure 14).

d. Area 3 (cm^2): The area of a rectangle was calculated by averaging the shoulder height and base of the tail height measurements, and multiplying by the body length measurement (Figure 14).

e. Area 4 (cm^2): The area of a rectangle was calculated by averaging chest depth and flank depth measurements, and multiplying by the body length measurement (Figure 14).

f. Area 5 (cm^2): The area of a rectangle was calculated by averaging the middle back height and base of the tail height measurements, and multiplying by the body length measurement (Figure 14).

g. Area 6 (cm^2): The area of a rectangle was calculated by averaging the trunk depth and flank depth measurements, and multiplying by the body length measurement (Figure 14).

Harvest Procedures

Study I. All pigs completing the study were sent for harvest at the University of Illinois Meat Science Laboratory when the pigs reached a live weight of ~125kg. Standard carcass grading data were collected postmortem including hot and cold carcass weight, backfat thickness at the first, tenth, and last rib, and at the last lumbar vertebra, *longissimus* muscle area at the tenth rib, and the carcass length measured from the cranial tip of the aitch bone to the last lumbar vertebra. Carcasses were fabricated into primal cuts and each primal cut was weighed.

Study II. All pigs completing the study were sent for harvest at the Beardstown plant of Cargill Meat Solutions when the mean pen weight reached ~117kg. Pigs were held in lairage for approximately 7 hours prior to harvest, without feed but with access to water. Pigs were harvested using standard procedures, after which the following carcass measurements were obtained: hot carcass weight, and backfat thickness and *longissimus* muscle depth measured using the Fat-O-Meter (model 87, American Tech, Inc., Dubuque, IA) and predicted carcass lean percentage.

Statistical Analysis

Regression analysis was carried out using the PROC REG procedures of SAS (2009), and the stepwise model selection option. Models were developed for the dependent variable live weight from start of the study (57.5 and 40.6 kg, for Study I and II, respectively), to marketing weight (126.6 kg, for both studies). The equations were chosen based on values of the adjusted R^2 and RSD, reporting the equation with the highest R^2 and the lowest RSD values. Weighing period biases (defined as the difference between predicted and measured live weight) were estimated by fitting the equations developed in Study I to the weight and body dimension data collected in Study II and vice versa. Also, genotype bias was estimated by fitting the equations developed in Study I to the data collected in Study II. Analysis of variance was carried out on the biases using PROC MIXED procedure of SAS (2009); the models used included sire line genotype (Duroc- and Landrace-based line), and weighing period (1 to 6) as fixed effects for the estimation of genotype bias and weighing period bias, respectively.

Table 1. Direct and calculated measurements taken on the live animal and on the dorsal and lateral photographs.

Item	Live animal (LA)	Dorsal photograph (PD)	Lateral photograph (PL)	Variables used in calculation
i. Direct measurements taken on the live animal and/or the photographs:				
Shoulder height	Yes	-	Yes	-
Body length	Yes	Yes	Yes	-
Shoulder width	Yes	Yes	-	-
Hip width	Yes	Yes	-	-
Chest circumference	Yes	-	-	-
Flank circumference	Yes	-	-	-
ii. Additional direct measurements taken on photographs:				
Chest width	-	Yes	-	-
Chest depth	-	-	Yes	-
Flank width	-	Yes	-	-
Flank depth	-	-	Yes	-
Cross shoulder to hip distance	-	Yes	-	-
Cross chest to flank distance	-	Yes	-	-
Middle back height	-	-	Yes	-
Base of tail height	-	-	Yes	-
Trunk depth	-	-	Yes	-
iii. Calculated measurements (from direct measurements):				
Shoulder cross-sectional area	Yes	-	-	Shoulder width (LA)
Shoulder circular dorsal area	-	Yes	-	Shoulder width (DP)
Hip cross-sectional area	Yes	-	-	Hip width (LA)
Hip circular dorsal area	-	Yes	-	Hip width (DP)
Chest cross-sectional area	Yes	-	-	Chest circumference (LA)
Chest circular dorsal area	-	Yes	-	Chest width (DP)
Flank area cross-sectional area	Yes	-	-	Flank circumference (LA)
Flank circular dorsal area	-	Yes	-	Flank width (DP)
Body area	Yes	Yes	-	Body length, Shoulder width, Hip width (LA &DP)
Chest/flank volume	Yes	-	-	Chest cross-sectional area, Flank cross-sectional area, Body length (LA)
Body volume	Yes	-	-	Shoulder cross-sectional area, Hip cross-sectional area, Body length (LA)
iv. Additional calculated measurements on photographs:				
Trunk area	-	Yes	-	Chest width, Flank width, Chest to flank distance, Body length (DP)
Area 1	-	-	Yes	Height to shoulder, Back height, Base of tail height, Body length (LP)
Area 2	-	-	Yes	Chest depth, Trunk depth, Flank depth, Body length (LP)
Area 3	-	-	Yes	Height to shoulder, Base of tail height, Body length (LP)
Area 4	-	-	Yes	Chest depth, Flank depth, Body length (LP)
Area 5	-	-	Yes	Back height, Base of tail height, Body length (LP)
Area 6	-	-	Yes	Trunk depth, Flank width, Body length (LP)

Figure 1: Shoulder height measurement.

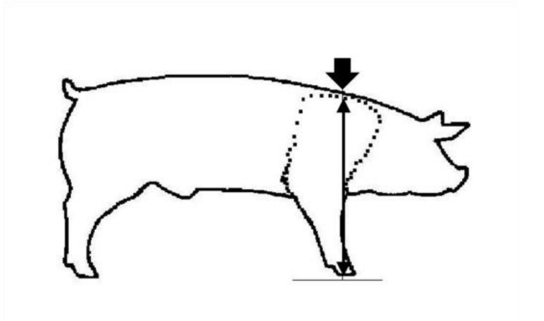


Figure 2: Body length measurement

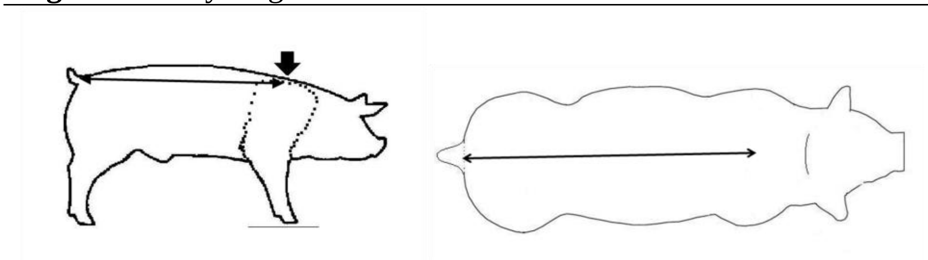
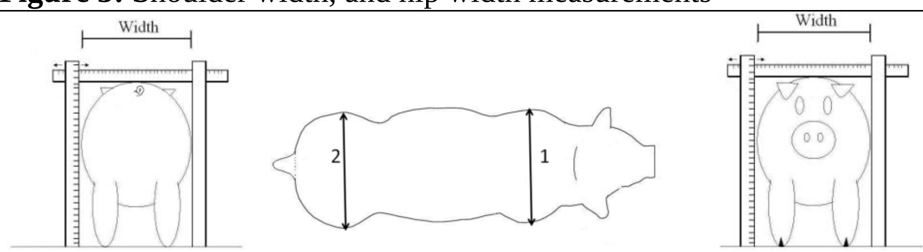


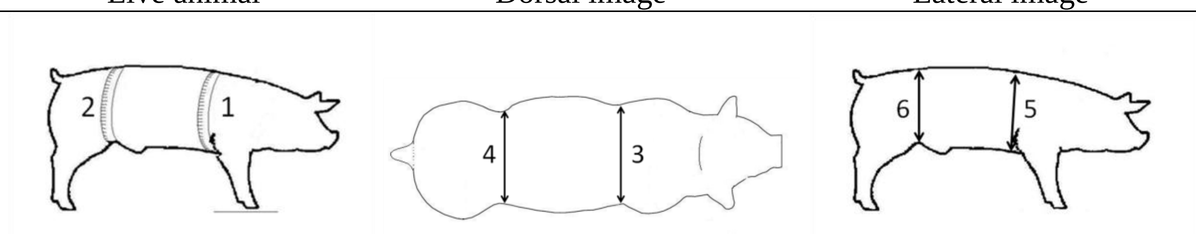
Figure 3: Shoulder width, and hip width measurements



1= Shoulder width; 2= Hip width

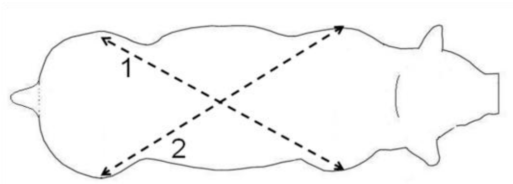
Figure 4: Chest and flank measurements

Live animal	Dorsal image	Lateral image



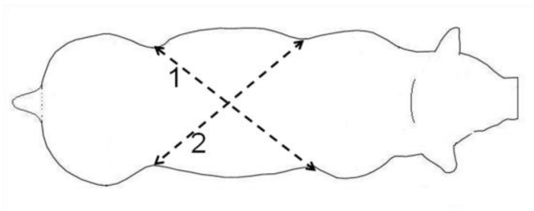
1= Chest circumference; 2 = Flank circumference; 3 = Chest width; 4 = Flank width; 5= Chest depth; 6 = Flank depth

Figure 5: Cross shoulder to hip distance.



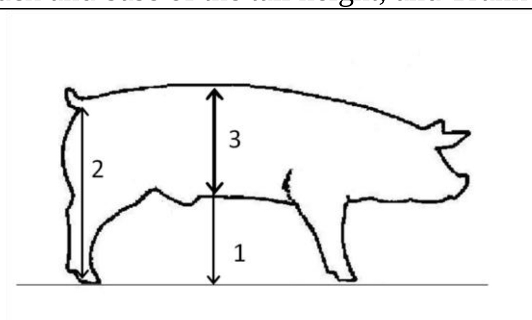
1= Left shoulder to right hip distance; 2= Right shoulder to left hip distance.

Figure 6: Cross chest to flank distance.



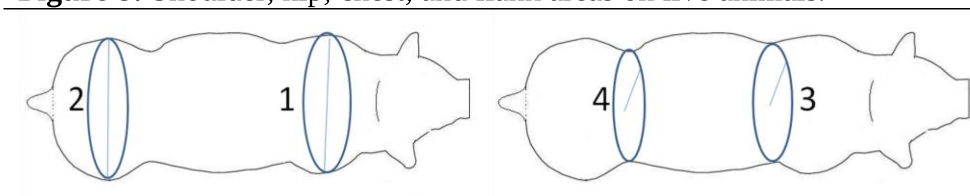
1= Left chest to right flank distance; 2= Right chest to left flank distance.

Figure 7: Middle back and base of the tail height, and Trunk depth measurements



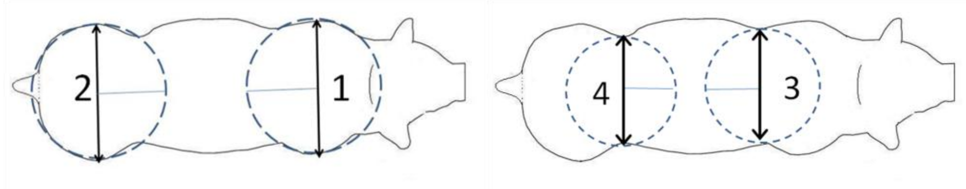
1=Middle back height 2= Base of the tail height 3= Trunk depth

Figure 8: Shoulder, hip, chest, and flank areas on live animals.



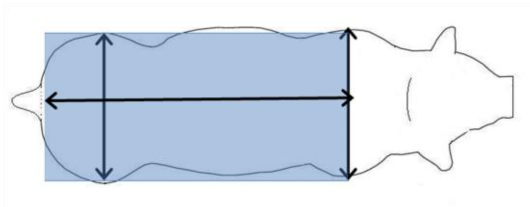
1= Shoulder area; 2=Hip area; 3= Chest area; 4= Flank area

Figure 9. Shoulder, hip, chest, and flank areas on photographs.



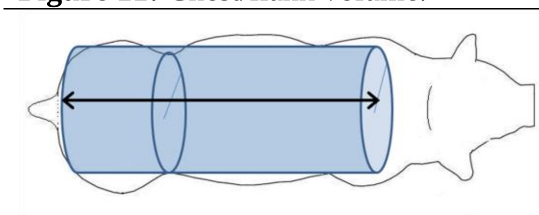
1= Shoulder area; 2=Hip area; 3= Chest area; 4= Flank area

Figure 10: Body area.[a]



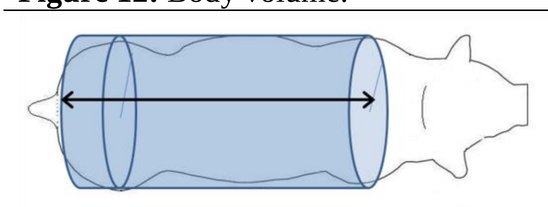
[a] Shaded portion represents the calculated area.

Figure 11: Chest/flank volume.[a]



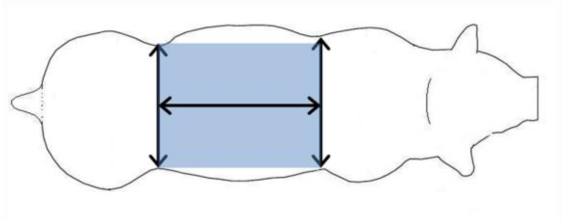
[a] Shaded portion represents the calculated volume.

Figure 12: Body volume.[a]



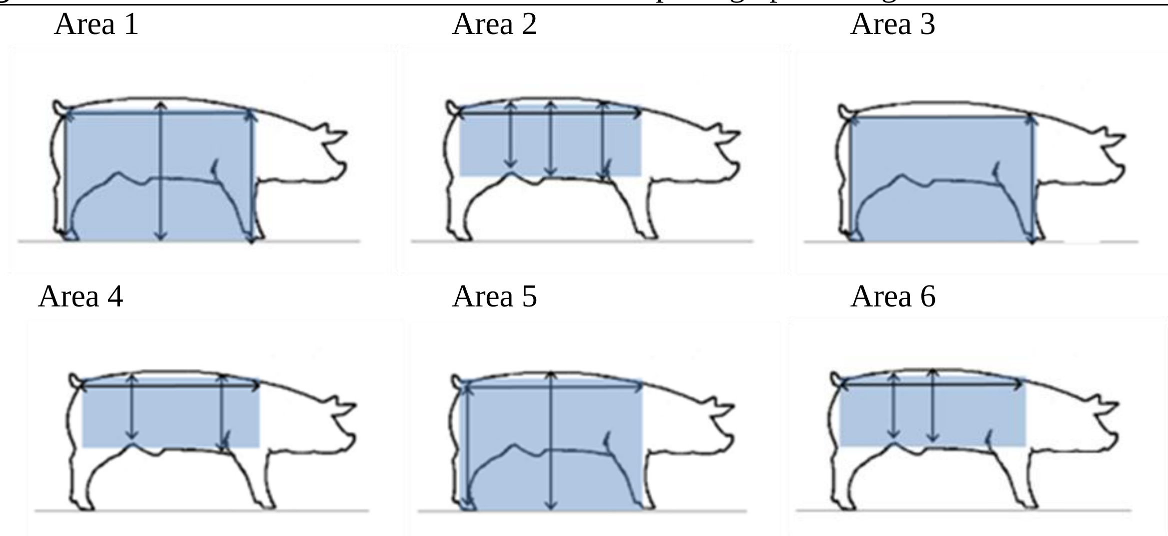
[a] Shaded portion represents the calculated volume.

Figure 13: Trunk area.[a]



[a] Shaded portion represents the calculated area.

Figure 14: Calculated measurements taken on lateral photographic images.[a]



[a] Shaded portion represents the calculated area.
Area 1 = chest to flank distance (chest width + flank width)/2; Area 2 = body length (chest depth + trunk depth + flank depth)/3; Area 3 = body length (shoulder height + base of the tail height)/2; Area 4 = body length (chest depth + flank depth)/2; Area 5 = body length (middle back height + base of the tail height)/2; Area 6 = body length (trunk depth + flank depth)/2.

RESULTS AND DISCUSSION

Summary statistics for the variables measured in both studies are presented in Table 2 and regressions equations for the relationship between live weight and various individual body measurements are presented in Table 3. The data came from two different studies with 72 animals in Study 1 and 144 animals in Study 2. The weight range in both studies was similar, with an average start weight of 57.5 kg (SD = 7.11kg) and average end weight of 134 kg (SD = 4.27kg) for Study 1, and an average start weight of 53.7 kg (SD = 5.78 kg), and average end weight of 134 kg (SD = 8.42kg) for Study 2.

Within any study, the accuracy of prediction of regression equations can be compared using the R^2 values and this will be the focus of the discussion of the equations generated in this research.

Comparison Between Studies

There were similarities between the two studies for equations based on same direct measurements taken on the live animal and also for calculated measurement based on the direct measurements. Examples of similar R^2 values for equations based on measurements taken on live animals between Study 1 and Study 2 include shoulder height (R^2 = 0.84 and 0.85, respectively), chest circumference (0.93 and 0.95, respectively), body area (0.93 and 0.95, respectively), and body volume (0.93 and 0.94, respectively). On the other hand, there were differences between the two studies for the R^2 values for equation for some measurements taken on the live animal such as body length (0.44 and 0.26 for Studies 1 and 2, respectively) and body area (0.63 and 0.45, respectively). Differences between studies in R^2 values for predictions equations were more marked for equations based on dorsal and lateral photographs. Generally speaking, R^2 values from equations based on dorsal photographs in Study 1 were higher than for the equivalent measurement in Study 2. For example, trunk area had a R^2 of 0.82 and 0.66 for Study 1 and Study 2, respectively; similarly, R^2 for body area were 0.63 and 0.45, respectively and for hip width were 0.64 and 0.50, respectively. In contrast, R^2 values for equations based on lateral photographs in Study 2 were lower than the equivalent measurement in Study 1. Examples of differences in R^2 values between Study 1 and 2 for equations based on measurements taken on lateral photographs include shoulder height (0.26 and 0.65, respectively), and lateral trunk area (0.67 and 0.82, respectively). Two possible reasons for these differences between the studies include potential differences in the behavior and posture of the animals during measurement and the taking of the photographs. In Study 2 the pigs were kept in groups and were generally easier to handle than those from Study 1 that were housed in individual pens and, consequently, it is possible that the measurements taken on the lateral photographs from Study 2 were more accurate and repeatable than those from Study 1. Also, although all of the measurements taken on the photographs were carried out by the same operator, a considerable amount of time elapsed between the studies which could have resulted in changes in the way the photographs were measured, particularly for those measurements, such as body length or chest to flank measurements that lack easily identifiable anatomic points.

Because of these differences between studies, the following presentation of results and discussion will highlight important differences in regression relationships between studies.

Comparison of Equations Based on Live Animals and Photographs

In general, regression equations to predict live weight based on measurements taken on the live animals had higher R^2 values than those based on measurement taken on photographs. For example, in Study 2 the equation based on the shoulder height measurement taken on the live animal had a R^2 of 0.85, while equation based on the same measurement taken on lateral photographs had a R^2 of 0.65. Similarly, the regression equations based on body length from Study 1 had a R^2 of 0.82 for the live animal measurement compared R^2 for equations based on dorsal and lateral photographs of 0.44 and 0.40, respectively. These results are in agreement with those obtained by Phillips and Dawson (1936) who studied the accuracy of different methods to predict live weight of pigs, and found that using calipers and measuring tape to measure the length and height of the live animals was more accurate than the measurements of different parts of the body taken on photographs.

Comparison Between Dorsal and Lateral Photographs

Although the R^2 obtained from equations based on measurements taken on the live animal were generally higher than the R^2 values of equations based on measurements taken on photographs, equations for some measurements taken on photographs still yielded relatively high R^2 values. Equations based on measurements taken on the photographs with high R^2 values included a number taken on the dorsal photographs in Study 1 including trunk area (R^2 = 0.82), flank circular dorsal area (0.79) and flank width (0.79). In addition, equations with high R^2 values based on measurements taken on lateral photographs in Study 2 included those based on Lateral Area 2 (0.82) and Lateral Area 4 (0.83). Generally speaking, R^2 values obtained from the equations based on measurements taken on dorsal photographs were lower than those from other studies where similar measurements were taken on photographs using different image analysis systems. For example, Brandl and Jøergensen (1996) used a semi-automatic system to analyze video frames of the dorsal view of the pigs, and obtained R^2 values of 0.96 for equations based on the measurement of body length. In addition, Brandl and Jøergensen (1996) found R^2 values of 0.95 and 0.97 for equations based on hip width and shoulder width, respectively. However, the study by Brandl and Jøergensen (1996) did not report residual standard deviations (RSD) that could allow a comparison between their results and those obtained in the present two studies. Also, White et al. (2004), using a visual image analysis (VIA) system, obtained an R^2 value of 0.91 (RSD = 6.2 kg) for the equation based on the measurement of the total dorsal plan area of the body, excluding the head. The area measured by White et al. (2004) was similar to the body area measured on photographs in the current studies which in Study 2 gave a maximum R^2 of 0.63 and a RSD of 15.8 kg. The use of more sophisticated and sensitive systems for image collection and analysis can be one of the reasons for these differences between the current study and that of White et al. (2004). Unfortunately, no published study has used similar measurements on lateral images of pigs to those used in the present study to allow a comparison of results. However, the higher R^2 values obtained in the present study for equations based on measurements taken on lateral compared to dorsal photographs suggests that further research in this area is warranted.

Comparison Between Direct Measurements and Calculated Measurements

The highest R^2 values obtained in both studies were generated by regression equations based on circumference measurements taken directly on the animal. For example, chest circumference and flank circumference from Study 2 had R^2 values of 0.95 and 0.94, respectively; for Study 1 the same measurements had R^2 values of 0.93 and 0.85, respectively. There is limited published information in the scientific literature addressing the relationship between live weight and chest or flank circumference in pigs. However, results from studies carried out with different species have also shown that such measures are relatively accurate predictors of live weight (Heinrichs et al., 1992; Dingwell et al., 2006). However, despite the accuracy of prediction of live weight from circumference measures, their use is limited by the practical problems associated with taking the measurements, which is supported by the statement made by Brandl and Jørgensen (1996) that the measurement of either chest or flank circumference were relatively easy to perform and not too time consuming, but they still required the immobilization of the pig.

Two important results can be seen when comparing the R^2 values obtained from regression equations based on direct measurements and regression equations based on calculated measurements. Firstly, some of the regression equations that are based on calculated measurements with several direct measurements involved in their estimation had higher R^2 values than those generated by the regression equations based on the individual direct measurements that were components of the calculated measurements. For example, in Study 2, the regression equation for the calculated measurement of body area gave a greater R^2 value (0.95) than that for the component measurements of body length (0.88), shoulder width (0.86), and hip width (0.88). Similarly, in Study 2, Area 4 yielded a R^2 value of 0.83, while the measurements used to calculate this, body length, chest depth, and flank depth yielded R^2 values of 0.65, 0.77, and 0.72, respectively. However, this does not apply to all calculated measurements that used direct measurements in their estimation. In fact, the R^2 values of some calculated measurements had similar or lower R^2 values than those values generated by the regression equations of the measurements that were used in their calculation. For example, the regression equation based on the measurement of chest/flank volume in Study 1 had a R^2 value of 0.93, which is similar to the R^2 values obtained from the equations of two of the three direct measurements used in its calculation, namely cross-sectional chest area (R^2 = 0.95), and cross-sectional flank area (R^2 = 0.94), with the third measurement, body length, giving a lower R^2 value (0.88).

In addition, the regression equations from calculated measurements based on a single direct measurement gave similar R^2 values to those obtained from the equations for the single measurement. For example, the R^2 of the calculated measurement cross-sectional chest area in Study 2 was 0.95 which was identical to that for the equation for the direct measurement of chest circumference that was the only measurement used in its estimation. Also, in Study 1, the R^2 for the equations for calculated measurements of cross-sectional flank area was similar to that for flank circumference that was used in its estimation (0.86 and 0.85, respectively).

Weight Range and Genotype Bias

According to Gu et al. (1992), when prediction models are selected, is important to consider bias(es) of the equations and not only the precision (R^2). Gu (1992) also pointed out that an equation with a high R^2 could be associated with large genotype and/or weight range bias. Weight range biases for equations developed in Study 1 and 2 are summarized in Tables 4 and 5, respectively, and sire line biases are summarized in Table 6. The regression equations developed in Study 1 were used to predict live weight for pigs in Study 2 based on the measurements taken in Study 2 at each weight period and these predicted values were compared with the actual weight. Bias was calculated as (Actual value – Predicted value). Positive bias suggests that the equation underestimates live weight, and negative bias suggests the opposite. Analysis of variance was performed to determine the effect of weight range and genotype on bias of predicted weights. There were significant differences ($P < 0.05$) between the biases for the various weight ranges in Studies 1 and 2 (Tables 4 and 5, respectively), and between the biases for sire line in Study 2 (Table 6).

Generally speaking, the greatest weight range and sire line bias were shown on equations based on measurements taken on dorsal images with equations based on live animals, and lateral images having the lowest biases. Most equations from both studies tended to overestimate live weight at the lightest weight ranges, and to underestimate at the heaviest weight ranges. For example, with the exception of chest to flank volume, all the equations developed in Study 2 overestimated the weight of the animals of Study 1 (Table 5) during the first weight range (57.5 kg, SD = 7.11 kg). This extent of this overestimation was reduced for subsequent weight periods. Also, with the exception of shoulder height, chest depth, middle back height, and base of the tail height, all the equations based on measurements taken on lateral photographs developed in Study 1, had bias values close to ± 5 kg for the heaviest weight range when the weight of animals in Study 2 was estimated (Table 4). In addition, other equations showed a bias close to ± 5% of the actual weight in the final weight range. For example, the equations developed in Study 1 based on the measurements taken on live animals body area and shoulder width, predicted the weight of animals in Study 2 with a bias of 1.4% and 3.1% of the actual weight during the heaviest weight range (Table 4). However, most of the equations developed in both studies and based on dorsal photographs underestimated live weight, with the only exception of the equation developed in Study 1 based on shoulder area, which showed a bias within ± 5% of the actual weight of the animals in Study 2.

In contrast, three prediction equations developed in Study 1 based on measurements taken on live animals had relatively low biases between weight periods when predicting the weight of the animals in Study 2 (Table 4). First, the weight period bias for the equation based on body volume was different ($P < 0.05$) across weight periods, however, the average bias was -1.15 kg. In addition, equations based on body area and body length were not different ($P > 0.05$) across weight periods and had average biases of 2.03 kg and 2.51 kg, respectively.

Weight range bias was shown as an important factor to be considered when selecting the appropriate model. For instance, a large number of equations were able to predict live weight within 5% of the actual weight during the heaviest weight ranges (120.4 and 126 kg for Study 1, and 112.7 and 126.6 kg for Study 2). While other equations predicted live weight within ± 5% of the actual weight across all the different weight ranges (e.g. body volume, body area, and body length from Study 1). Ideally, the weight range of the animals to be measured should be considered when selecting the most adequate prediction model. However, when equations are to be used to predict the weight of animals across a wide range, the equation of preference should be one that has the lowest biases across the required weight range.

Generally speaking, genotype bias was low for most of the equations and, although the differences in genotype bias were significant ($P < 0.05$) for a number of equations, the difference in predicted weight between lines was not relevant from a practical standpoint (Table 6). However, the genotype bias should be taken into account for the equations based on the measurements of chest circular dorsal area and chest width, taken on dorsal images. Comparing the predicted weight of Duroc- vs. Landrace-based lines, these two equations estimated a heavier live weight (6.27 and 6.06 kg, for chest circular dorsal area, and chest width, respectively) in the Duroc-based lines. Therefore, some of the landrace-based equations from Study 1 were able to predict live weight within 5% of the actual weight for both the Duroc- and Landrace-based lines used in Study 2. Nevertheless, it is important to consider that the prediction weight could be affected by the genotype of the animals, and therefore, the equation to be selected should be, preferably, one that was developed the genotype in question or an equation that is not affected by genotype.

CONCLUSIONS

The present studies demonstrate that live weight of grow to finishing pigs can be accurately predicted by a number of regression equations based on the measurements of different parts of the body of animals. In order to select the most appropriate equation, it is important to consider the two following factors: First, in agreement with Gu et al. (1992), the elimination of bias should be the primary concern in model selection, while the R^2 ought to be considered as a secondary issue. The reason for that, according to Gu et al. (1992), is that the R^2 can be improved by increasing the sample size and/or increasing the number of replicates, but they will not improve or eliminate the biases in the predictions. In this case, the "optimum" equation will be the one that gives the lowest genotype and weight range biases. The second factor to be considered is the practicality of the measurements. Many measurements were as time consuming as the use of a weighing scale, and also required the restraining of the animals. Therefore, the use of these measurements in the production site under commercial conditions could be compromised due to those limitations. For example, the equations based on body area and body volume from Study 1, could be considered as two of the best options because they showed a low bias due to genotype and weight range. However, they required several measurements for their calculation and therefore, their practical use is limited. Nevertheless, measurements taken directly on the animal such as hip width and shoulder width, were easy to measure, did not require restraining of the animal, and were able to accurately predict the weight of the animals.

From a practical standpoint and due to the large number of animals in commercial production sites, it is unlikely that the selection of market animals can be solely based on the methods presented in this study, even on those that were easy to take. Conversely, their use should be focused more as a complementary tool to assist on the visual appraisal selection. For instance, the use of one or more measurements can be used to either calibrate the operator visual appraisal to the existing animals and/or to check that the selected animals are in the desired weight range.

On the other hand, the use of methodologies based on photograph image analysis could be more of interest from the research standpoint, due to their non-invasive approach. For example, in experiments intended to study the behavior of the animals, measurements taken on photographs can give a close prediction of the animal weight without altering the behavior of the animal.

REFERENCES

Augspurer, N. R. and M, Ellis. 2002. Weighing affects short-term feeding patterns of growing-finishing pigs. Can. J. Anim. Sci. 82: 445-448.

Bewley, J.M., A.M. Peacock, O. Lewis, R.E. Boyce, D.J. Roberts, M.P. Coffey, S. J. Kenyon, and M. M. Schutz. 2008. Potential for estimation of body condition scores in dairy cattle from digital images. J. Dairy Sci. 91: 3439-3453.

Brandl, N., and E. Jørgensen. 1996. Determination of live weight of pigs from dimensions measured using image analysis. Computers and Electronics in Agriculture 15(1):57-72.

Brody, S. 1945. Bionergetics and Growth. Reinhold, New York.

Dingwell, R., M. Walace, C. McLaren, C. Leslie, and K. Leslie. 2006. An evaluation of two indirect methods of estimating body weight in Holstein calves and heifers. J. Dairy Sci. 89:3992-3998.

Doeschl, A.B., D.M. Green, C.T. Whittemore, C.P. Schofield, A.V. Fisher, and P.W.Knap. 2004. The relationships between the body shape of living pigs and their carcass morphology and composition. Animal Science 79: 73-83.

Donovan, G. A., and R. K Braun. 1987. Evaulation fo dairy heifer replacement rearing programs. Comp. Cont. Educ. Pract. Vet. 9:F133-F139.

Enevoldsen, C., and T. Kristensen. 1997. Estimation of body weight from body size measurements and body condition scores in dairy cows. J. Dairy Sci. 80:1988-1985.

Frost A.R., C.P. Schofield, S.A. Beaulah, T.T. Mottram, J.A. Lines, C.M. Wathes. 1997. A review of livestock monitoring and the need for integrated systems. Comput. Electron. Agric. 17:139-159.

Gu Y., A.P. Schinckel, T.G. Martin, J.C. Forrest, C.H. Kuei, and L.E. Watkins. 1992. Genotype and treatment biases in estimation of carcass lean of swine. J. Anim. Sci. 70:1708-1718.

Hammond, J. 1955. In: Progress in the Physiology of Farm Animals, Butterworths Scientific Publications. London, pp. 395–542.

Heinrichs, A. J., G.W. Rogers, and J.B. Cooper. 1992. Predicting body weight and wither height in Holstein heifers using body measurements. J. Dairy Sci. 75:3576-3581.

Lambe N.R., E.A. Navajas, C.P. Schofield, A.V. Fisher, G. Simm, R. Roehe, L. Bünger. 2008. The use of various live animal measurements to predict carcass and meat quality in two divergent lamb breeds. Meat Sci. 80:1138-1149.

McClure E. K., J. A. Scanga, K.E. Belk, and G.C. Smith. 2003. Evaluation of the E+V video image analysis system as a predictor of pork carcass meat yield. J. Anim. Sci. 81: 1193-1201.

Negretti P., G. Bianconi, S. Bartocci, S. Terramoccia, M. Verna. 2008. Determination of live weight and body condition score in lactating Mediterranean buffalo by Visual Image Analysis. Livestock Sci. 113: 1-7.

NRC. 1998. The Nutrient Requirements of Swine.10th ed, in National Research Council. National Academy Press, Washington. 1-189.

Phillips, R.W. and W.M. Dawson. 1936. A study of methods for obtaining measurements of swine. Anim. Prod. 29: 93-99.

Robinson, D.L. 2005. Assessing the accuracy of modeling weight gain of cattle using feed efficiency data. Livestock Prod. Sci. 95, 187-200.

Sarti, F.M., L Castelli, D. Bogani, and F. Panella. 2003. The measurement of chest girth as an alternative to weight determination in the performance recording of meat sheep. Ital. J. Anim. Sci. 2:123-129.

SAS Institute. 2009. SAS User's Guide: Statistics. SAS Inst. Inc., Cary, NC.

Schofield, C.P. 1990. Evaluation of image analysis as a means of estimating the weight of pigs. J. agric. Engng Res. 47:287-296.

Schofield, C.P., J.A. Marchant, R.P. White, N. Brand, M. Wilson. 1999. Monitoring pig growth using a prototype imaging system. J. Agric. Engng Res. 72, 205-210.

Shields, R.G., Jr.D.C. Mahan, and P.L. Graham.1983. Changes in swine body composition from birth to 145kg. J. Anim. Sci. 57:43-54.

Wang, Y., W. Yang, P. Winter and L.T. Walker. 2006. Non-contact sensing of hog weights by machine vision. Appl. Engin. in Agric. 22:577-582.

Wang Y., W. Yang., L Walker., T.M. Rababah. 2008.Enhancing the accuracy of area extraction in machine vision-based pig weighing through edge detection. Int. J. Agric Biol. Eng., 1: 37-42.

White, R.P., C.P. Schofield, D.M. Green, D.J. Parsons, and C.T. Whittemore. 2004. The effectiveness of visual image analysis (VIA) system for monitoring the performance of growing/finishing pigs. Animal Science 78:409-418.

Whittemore, C.T., and C.P. Schofield. 2000. A case for size and shape scaling for understanding nutrient use in breeding sows and growing pigs. Livestock Production Sci. 65: 203-208.

Wilson L.L., C.L. Egan, and T.L. Terosky. 1997. Body measurements and body weights of special-fed holstein veal calves. J. Dairy S. 80:3077-3082.

Wu J., R. Tillet, N. McFarlane, X. Ju, J.P. Siebert, P Schofield. 2004. Extracting the three-dimensional shape of live pigs using stereo photogrammetry. Comput. Electron. Agric. 44:203-222.

Yeo, M.L., and P.Smith. 1997. A note on relationships between girth measurements and sow liveweight gain. Exp. Husb. 33:81-84.

Yan, Y., and T. Guanghui. 2008, Estimating pig weight from 2D images. Computer and Computing Technologies in Agriculture. 2: 1471-1474.

TABLES OF RESULTS

Table 2. Descriptive statistics of live weight and direct and calculated measurements taken from the live animal and on dorsal and lateral photographs for Study I and II.

	Study I						Study II					
Item	N	Mean	SD	C.V.	Min	Max	N	Mean	SD	C.V.	Min	Max
Live weight, kg												
Start	72	57.5	7.11	12.4	36.8	76.9	144	53.7	5.78	10.8	39.0	67.0
End	72	134.0	4.27	3.2	111.1	147.3	142	126.7	8.42	6.7	98.0	147.5
Average	420	94.8	26.05	27.5	36.8	142.8	838	90.1	26.23	29.1	39.0	147.5
i. Direct measurements taken on the live animal and/or the photographs:												
Shoulder height, cm.												
Live animal	414	54.4	5.35	9.8	40.0	68.0	820	52.6	5.46	10.4	38.0	64.0
Lateral image	327	52.8	5.11	9.7	30.4	76.0	802	49.0	5.58	11.4	33.2	64.9
Body length, cm.												
Live animal	414	84.6	7.65	9.0	64.0	99.0	820	82.4	8.68	10.5	62.0	103.0
Dorsal image	419	65.8	6.54	9.9	43.6	79.1	838	68.3	5.69	8.3	52.0	87.8
Lateral image	325	68.6	5.33	7.8	50.6	81.4	803	68.0	7.94	11.7	48.3	93.8
Shoulder width, cm.												
Live animal	414	30.7	3.37	11.0	22.0	38.5	820	30.5	3.49	11.4	22.0	38.0
Dorsal image	420	28.4	2.94	10.4	19.0	35.8	838	29.0	2.75	9.5	21.5	36.7
Hip width, cm.												
Live animal	414	29.3	3.07	10.5	22.0	36.0	820	28.5	3.10	10.9	20.0	35.0
Dorsal image	420	27.7	2.56	9.2	21.1	35.0	838	28.0	2.34	8.1	20.0	35.0
Chest circumference, cm.												
Live animal	414	101.6	10.34	10.2	74.0	122.0	820	96.9	11.06	11.4	72.0	121.0
Flank circumference, cm.												
Live animal	414	102.8	9.06	8.8	74.0	121.0	820	96.1	10.27	10.7	71.0	119.0
ii. Additional direct measurements taken on photographs:												
Chest width, cm.												
Dorsal image	419	25.4	3.04	12.0	17.8	31.6	838	25.6	2.70	10.5	18.8	33.9
Chest depth, cm.												
Lateral image	327	32.4	3.37	10.4	24.1	41.6	799	30.0	3.78	12.6	20.7	41.4
Flank width, cm.												
Dorsal image	419	23.7	2.78	11.7	16.4	29.8	838	23.3	2.62	11.2	16.0	32.2
Flank depth, cm.												
Lateral image	327	35.2	3.60	10.2	26.0	43.1	801	34.4	4.35	12.6	22.9	49.2
Cross shoulder to hip distance, cm.												
Dorsal image	420	56.1	6.01	10.7	39.6	69.5	837	59.3	5.31	9.0	43.5	77.5
Cross chest to flank distance, cm.												
Dorsal image	419	40.0	4.45	11.1	29.1	50.2	836	41.8	4.13	9.9	30.5	53.0
Middle back height, cm.												

Table 2 (cont.)

Lateral image	327	59.7	5.15	8.6	36.7	74.7	803	57.6	6.40	11.1	38.3	77.8
Base of tail height, cm.												
Lateral image	326	50.8	4.13	8.1	38.1	62.4	802	50.3	5.89	11.7	34.2	71.0
Trunk depth, cm.												
Lateral image	326	38.5	3.37	8.8	30.3	48.6	802	37.1	4.05	10.9	27.2	51.5
iii. Calculated measurements (from direct measurements):												
Shoulder cross-sectional area, cm^2.												
Live animal	414	750.4	161.16	21.5	380.1	1164.2	820	738.7	166.01	22.5	380.1	1134.1
Shoulder circular dorsal area, cm^2.												
Dorsal image	420	640.3	128.28	20.0	282.4	1004.9	838	667.2	125.70	18.8	361.6	1060.1
Hip cross-sectional area, cm^2.												
Live animal	414	682.0	139.54	20.5	380.1	1017.9	820	644.6	137.81	21.4	314.2	962.1
Hip circular dorsal area, cm^2.												
Dorsal image	420	608.2	109.93	18.1	350.4	962.1	838	620.8	103.46	16.7	314.2	962.1
Chest cross-sectional area, cm^2.												
Live animal	414	830.3	164.73	19.8	435.8	1184.4	820	757.4	169.66	22.4	412.5	1165.1
Chest circular dorsal area, cm^2.												
Dorsal image	419	512.6	118.80	23.2	250.0	786.1	838	521.2	109.12	20.9	276.9	903.7
Flank cross-sectional area, cm^2.												
Live animal	414	848.2	146.17	17.2	435.8	1165.1	820	743.0	156.88	21.1	401.1	1126.9
Flank circular dorsal area, cm^2.												
Dorsal image	419	448.0	101.94	22.8	211.8	698.32	838	430.7	95.69	22.2	202.1	815.5
Body area, cm^2.												
Live animal	414	2558.5	466.82	18.2	1408.0	3456.0	820	2453.4	503.34	20.5	1408.0	3708.0
Dorsal image	419	1858.3	330.87	17.8	1077.6	2644.6	838	1958.4	310.78	15.9	1183.3	2959.1
Chest/flank volume, m^3.												
Live animal	414	0.0615	0.01691	27.5	0.0243	0.0100	820	0.0581	0.01774	30.5	0.0244	0.0105
Body volume, m^3.												
Live animal	414	0.0720	0.01854	25.8	0.0279	0.0108	820	0.0631	0.01949	30.9	0.0259	0.0109
Trunk area, cm^2.												
Dorsal image	417	993.7	209.35	21.1	516.9	1460.4	836	1029.3	197.89	19.2	594.1	1636.6
Area 1, cm^2.												
Lateral image	324	3743.1	501.23	13.4	2635	5337.1	801	3595.0	768.88	21.4	1973.0	6071.2
Area 2, cm^2.												
Lateral image	324	2432.3	363.66	15.0	1596.4	3429.7	796	2325.7	515.33	22.2	1267.9	4209.6
Area 3 cm^2.												

Table 2 (cont.)

Lateral image	324	3560.9	475.45	13.4	2497.1	4989.8	801	3414.5	734.82	21.5	1877.7	5984.2
Area 4, cm^2.												
Lateral image	324	2323.9	356.05	15.3	1520.4	3308.9	797	2216.6	504.70	22.8	1188.6	4063.7
Area 5, cm^2.												
Lateral image	324	3801.5	511.78	13.5	2596.5	5514.9	802	3707.8	797.52	21.5	2091.3	6271.9
Area 6, cm^2.												
Lateral image	324	2534.7	383.08	15.1	1624.3	3573.5	800	2456.9	541.88	22.1	1326.4	4438.8

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

Table 3. Single variable regression equations for predicting live weight for Study I and II

Item	Study I				Study II			
	Intercept	Slope	R^2	RSD	Intercept	Slope	R^2	RSD
i. Direct measurements taken on the live animal and/or the photographs:								
Shoulder height, cm.								
Live animal	-150.17	4.499	0.84	10.5	-142.75	4.435	0.85	10.0
Lateral image	-10.261	2.103	0.26	18.2	-92.104	3.730	0.65	15.2
Body length, cm.								
Live animal	-167.25	3.098	0.82	11.2	-142.63	2.829	0.88	9.2
Dorsal image	-78.328	2.630	0.44	19.6	-71.993	2.372	0.26	22.5
Lateral image	-71.280	2.506	0.40	16.4	-98.595	2.782	0.73	13.3
Shoulder width, cm.								
Live animal	-123.17	7.09	0.83	10.8	-121.73	6.966	0.86	9.9
Dorsal image	-108.86	7.17	0.65	15.3	-117.45	7.152	0.56	17.3
Hip width, cm.								
Live animal	-136.64	7.893	0.85	10.1	-135.52	7.937	0.88	9.1
Dorsal image	-131.54	8.168	0.64	15.5	-131.71	7.915	0.50	18.6
Chest circumference, cm.								
Live animal	-153.74	2.445	0.93	7.10	-133.65	2.313	0.95	5.7
Flank circumference, cm.								
Live animal	-180.09	2.672	0.85	10.1	-146.96	2.472	0.94	6.5
ii. Additional direct measurements taken on photographs:								
Chest width, cm.								
Dorsal image	96.505	7.546	0.78	12.3	-105.68	7.641	0.62	16.2
Chest depth, cm.								
Lateral image	-50.720	4.677	0.56	14.0	-88.945	5.992	0.77	12.4
Flank width, cm.								
Dorsal image	-102.80	8.331	0.79	12.0	-101.82	8.246	0.68	14.9
Flank depth, cm.								
Lateral image	-57.490	4.500	0.59	13.5	-81.760	5.006	0.72	13.7
Cross shoulder to hip distance, cm.								
Dorsal image	-96.427	3.410	0.62	16.1	-106.75	3.318	0.45	19.5
Cross chest to flank distance, cm.								
Dorsal image	-99.615	4.856	0.69	14.6	-103.04	4.624	0.53	18.0
Middle back height, cm.								
Lateral image	-48.260	2.494	0.37	16.8	-96.805	3.275	0.65	15.2
Base of tail height, cm.								
Lateral image	-23.319	2.441	0.22	18.6	-84.363	3.477	0.63	15.7
Trunk depth, cm.								
Lateral image	-86.48	4.859	0.60	13.3	-107.78	5.352	0.71	13.9
iii. Calculated measurements (from direct measurements):								
Shoulder cross-sectional area, cm^2.								
Live animal	-16.308	0.148	0.82	11.0	-17.475	0.146	0.86	9.9
Shoulder circular dorsal area, cm^2.								
Dorsal image	-10.202	0.164	0.65	15.4	-13.274	0.155	0.55	17.6
Hip cross-sectional area, cm^2.								
Live animal	-23.657	0.174	0.85	10.1	-24.332	0.178	0.88	9.2
Hip circular dorsal area, cm^2.								
Dorsal image	-20.147	0.189	0.64	15.7	-19.654	0.177	0.49	18.8
Chest cross-sectional area, cm^2.								
Live animal	-32.852	0.154	0.93	7.0	-23.743	0.151	0.95	5.6
Chest circular dorsal area, cm^2.								
Dorsal image	-3.815	0.192	0.77	12.4	-7.466	0.187	0.61	16.5
Flank cross-sectional area, cm^2.								

Table 3 (cont.)

Live animal	-46.116	0.166	0.86	9.9	-29.604	0.162	0.94	6.6
Flank circular dorsal area, cm^2.								
Dorsal image	-6.775	0.227	0.79	12.1	-6.075	0.223	0.66	15.2
Body area, cm^2.								
Live animal	-43.965	0.054	0.93	7.0	-33.927	0.051	0.95	5.9
Dorsal image	-21.379	0.063	0.63	15.8	-20.668	0.057	0.45	19.5
Chest/flank volume, m^3.								
Live animal	-3.831	1368.6	0.93	6.7	7.057	1323	0.97	4.8
Body volume, m^3.								
Live animal	2.696	1496.3	0.93	7.0	7.175	1434.2	0.94	6.2
Trunk area, cm^2.								
Dorsal image	-16.999	0.113	0.82	11.1	-21.016	0.108	0.66	15.3
Area 1, cm^2.								
Lateral image	-12.747	0.030	0.51	14.8	-16.561	0.030	0.79	11.7
Area 2, cm^2.								
Lateral image	-15.374	0.048	0.67	12.2	-14.589	0.045	0.82	10.9
Area 3 cm^2.								
Lateral image	-9.695	0.031	0.48	15.2	-15.704	0.031	0.79	11.8
Area 4, cm^2.								
Lateral image	-13.126	0.049	0.68	12.0	-12.096	0.046	0.83	10.7
Area 5, cm^2.								
Lateral image	-10.214	0.029	0.50	15.0	-15.291	0.029	0.78	12.0
Area 6, cm^2.								
Lateral image	-11.528	0.044	0.64	12.7	-13.840	0.043	0.80	11.4

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

Table 4. Weight range biases (kg) for predicting live weight by fitting the measurements from Study 2 into the prediction equations developed in Study 1.

Item	Weight range bias						SEM	P-value
	1	2	3	4	5	6		
Weight, kg.	53.7	67.9	83.2	98.6	112.7	126.6	-	-
i. Direct measurements taken on the live animal and/or the photographs:								
Shoulder height.								
Live animal .	1.19^{c}	1.20^{c}	3.12^{c}	0.96^{c}	6.29^{b}	11.02^{a}	0.805	0.001
Lateral image.	-26.82^{e}	-15.44^{e}	-7.32^{d}	5.75^{c}	14.67^{b}	17.09^{a}	0.821	0.001
Body length.								
Live animal.	2.68^{ab}	0.63^{b}	2.51^{ab}	3.31^{a}	1.90^{ab}	4.03^{a}	0.804	0.059
Dorsal image.	25.87^{e}	34.46^{d}	35.66^{d}	46.18^{c}	50.56^{b}	83.34^{a}	1.147	0.001
Lateral image.	-19.89^{d}	-14.12^{c}	-12.19^{c}	-6.77^{b}	0.84^{a}	3.24^{a}	1.110	0.001
Shoulder width.								
Live animal.	-6.77^{e}	-2.49^{c}	-5.49^{de}	-3.57^{cd}	0.49^{b}	3.90^{a}	0.786	0.001
Dorsal image.	-22.65^{e}	-15.86^{d}	-14.45^{cd}	-12.07^{c}	-4.88^{b}	16.35^{a}	1.030	0.001
Hip width.								
Live animal.	-1.00^{c}	0.49^{c}	-0.40^{c}	0.93^{c}	4.65^{b}	9.68^{a}	0.716	0.001
Dorsal image.	-22.10^{e}	-15.61^{d}	-14.46^{d}	-7.17^{c}	-3.78^{b}	21.08^{a}	1.050	0.001
Chest circumference.								
Live animal.	8.41^{a}	7.75^{ab}	6.65^{bc}	5.29^{c}	6.78^{b}	8.65^{a}	0.496	0.001
Flank circumference.								
Live animal.	13.64^{ab}	14.69^{a}	14.98^{a}	12.87^{b}	12.64^{b}	14.68^{a}	0.574	0.009
ii Additional direct measurements taken on photographs:								
Chest width.								
Dorsal image.	-18.15^{e}	-12.29^{d}	-13.15^{d}	-9.16^{c}	-3.36^{b}	16.61^{a}	0.990	0.001
Chest depth.								
Lateral image.	-15.20^{e}	-9.19^{e}	-0.29^{d}	7.46^{c}	13.64^{a}	10.12^{b}	0.929	0.001
Flank width.								
Dorsal image.	-8.68^{d}	-6.36^{d}	-6.13^{d}	-3.37^{c}	-0.20^{b}	19.59^{a}	0.980	0.001
Flank depth.								
Lateral image.	-22.53^{e}	-12.80^{d}	-8.46^{c}	-4.07^{b}	3.47^{a}	3.28^{a}	1.421	0.001
Cross shoulder to hip distance.								
Dorsal image.	-31.31^{e}	-25.21^{d}	-24.11^{d}	-18.07^{c}	-9.79^{b}	15.04^{a}	1.040	0.001
Cross chest to flank distance.								
Dorsal image.	-24.60^{d}	-19.61^{c}	-20.96^{c}	-18.80^{c}	-8.49^{b}	14.98^{a}	1.036	0.001
Middle back height.								
Lateral image.	-24.90^{e}	-14.18^{d}	-7.66^{c}	0.38^{b}	9.89^{a}	9.85^{a}	0.993	0.001
Base of tail height.								
Lateral image.	-31.21^{e}	-18.42^{e}	-12.14^{d}	-5.35^{c}	5.52^{b}	9.76^{a}	1.020	0.001
Trunk depth.								
Lateral image.	-17.31^{e}	-11.54^{e}	-3.33^{d}	0.25^{c}	9.14^{a}	4.80^{b}	1.203	0.001
iii Calculated measurements (from direct measurements):								
Shoulder cross-sectional area.								
Live animal	-8.25^{d}	-2.74^{c}	-4.57^{c}	-2.85^{c}	0.64^{b}	2.85^{a}	0.790	0.001
Shoulder circular dorsal area.								
Dorsal image	-42.78^{d}	-35.65^{c}	-34.33^{c}	-32.72^{c}	-26.43^{b}	-4.30^{a}	1.080	0.001
Hip cross-sectional area.								
Live animal	-3.21^{d}	-0.03^{c}	0.22^{c}	1.57^{c}	4.75^{b}	8.94^{a}	0.713	0.001
Hip circular dorsal area.								
Dorsal image	-22.15^{d}	-15.18^{c}	-13.99^{c}	-6.91^{b}	-4.46^{b}	21.37^{a}	1.090	0.001
Chest cross-sectional area.								
Live animal	5.15^{c}	6.80^{ab}	7.14^{ab}	6.16^{bc}	7.16^{ab}	7.95^{a}	0.479	0.001
Chest circular dorsal area.								
Dorsal image	-18.07^{e}	-11.58^{cd}	-12.29^{d}	-8.77^{c}	-4.05^{b}	16.70^{a}	1.040	0.001
Flank cross-sectional area.								
Live animal	9.94^{d}	13.13	15.04^{a}	13.78^{abc}	13.41^{bc}	14.75^{ab}	0.540	0.001
Flank circular dorsal area.								
Dorsal image	-9.98^{e}	-6.10	-5.33^{cd}	-2.65^{bc}	-0.50	19.90^{a}	1.000	0.001

Table 4 (cont.)

Body area.								
Live animal.	2.19	3.13	2.23	1.83	1.04	1.76	0.525	0.13
Dorsal image.	-25.90[d]	-18.65[c]	-18.95[c]	-12.45[b]	-9.55[b]	21.23[a]	1.050	0.001
Chest/flank volume.								
Live animal.	9.63[e]	13.93[d]	14.88[cd]	15.95[bc]	16.74[ab]	17.76[a]	0.490	0.001
Body volume								
Live animal.	-0.11[b]	1.49[a]	2.21[a]	-0.42[b]	-3.85[c]	-6.26[d]	0.429	0.001
Trunk area								
Dorsal image.	-16.39[d]	-12.19[c]	-14.98[d]	-14.52[cd]	-9.03[b]	14.62[a]	0.940	0.001
Area 1.								
Lateral image.	-13.66[d]	-6.29[c]	-5.42[c]	-1.62[b]	3.71[a]	-1.52[b]	1.056	0.001
Area 2.								
Lateral image.	-12.12[d]	-7.14[c]	-5.20[bc]	-3.52[b]	0.86[a]	-6.26[bc]	1.069	0.001
Area 3.								
Lateral image.	-15.16[d]	-7.46[c]	-6.67[c]	-2.50[b]	2.74[a]	-2.04[b]	1.059	0.001
Area 4.								
Lateral image.	-11.54[d]	-6.13[c]	-4.51[bc]	-2.35[b]	1.48[a]	-5.36[c]	1.061	0.001
Area 5.								
Lateral image.	-16.10[e]	-8.36[d]	-7.35[cd]	-4.78[bc]	1.32[a]	-3.02[b]	1.091	0.001
Area 6.								
Lateral image.	-13.84[d]	-8.00[c]	-5.96[bc]	-4.29[b]	1.08[a]	-4.36[b]	1.103	0.001

[abcde] Values with different superscripts within a row indicate effect of weight range in predicted errors.
Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

Table 5. Weight range biases (kg) for predicting live weight by fitting the measurements from Study I into the prediction equations developed in Study 2.*

Item	Weight range bias						SEM
	1	2	3	4	5	6	
Weight, kg.	57.5	72.9	89.8	106.3	120.4	126.6	-
i. Direct measurements taken on the live animal and/or the photographs:							
Shoulder height.							
Live animal.	-9.24^{a}	-7.12^{ab}	-5.32^{bc}	-2.22^{cd}	-1.00^{de}	2.10^{e}	1.176
Lateral image.	-	-19.87^{a}	-8.50^{b}	1.47^{c}	5.66^{c}	6.26^{c}	2.123
Body length.							
Live animal.	-43.79^{a}	-45.23^{a}	-38.02^{b}	-30.38^{c}	-22.28^{d}	-21.61^{d}	0.995
Dorsal image.	-8.82^{a}	-3.71^{b}	3.10^{c}	15.07^{d}	30.96^{e}	30.12^{e}	1.445
Lateral image.	-	-5.97^{a}	2.41^{b}	7.96^{c}	18.69^{d}	26.20^{e}	1.570
Shoulder width.							
Live animal.	-2.17^{a}	-2.86^{a}	-3.19^{a}	6.32^{b}	5.17^{b}	12.71^{c}	1.114
Dorsal image.	5.18^{c}	-4.76^{a}	-0.23^{b}	10.77^{d}	23.25^{e}	22.71^{e}	1.334
Hip width.							
Live animal.	-4.47^{bc}	-8.55^{a}	-5.76^{ab}	-2.10^{c}	1.08^{d}	6.80^{e}	1.072
Dorsal image.	1.57^{c}	-6.69^{a}	-2.58^{b}	8.38^{d}	21.00^{e}	23.95^{e}	1.277
Chest circumference.							
Live animal.	-8.60^{b}	-12.55^{a}	-9.11^{b}	-5.65^{c}	-2.12^{d}	-1.34^{d}	0.739
Flank circumference.							
Live animal.	-19.84^{a}	-19.45^{a}	-15.84^{b}	-10.10^{c}	-5.56^{d}	-3.13^{d}	0.965
ii Additional direct measurements taken on photographs:							
Chest width.							
Dorsal image.	2.64^{b}	-2.78^{a}	0.51^{ab}	8.92^{c}	12.96^{cd}	17.58^{d}	1.657
Chest depth.							
Lateral image.	-	-12.26^{a}	-4.76^{b}	-3.94^{bc}	1.24^{d}	0.64^{cd}	3.816
Flank width.							
Dorsal image.	-2.00^{b}	-8.15^{a}	-5.65^{a}	5.28^{c}	6.55^{c}	12.00^{d}	1.164
Flank depth.							
Lateral image.	-	-1.52^{a}	3.04^{b}	4.71^{b}	14.21^{c}	17.13^{c}	-7.513
Cross shoulder to hip distance.							
Dorsal image.	8.06^{b}	2.85^{a}	6.73^{ab}	17.31^{c}	28.41^{d}	31.87^{d}	1.422
Cross chest to flank distance.							
Dorsal image.	6.18^{b}	1.20^{a}	5.40^{b}	15.92^{c}	23.22^{d}	26.74^{d}	1.348
Middle back height.							
Lateral image.	-	-12.14^{a}	-3.23^{b}	5.72^{c}	11.58^{d}	12.66^{d}	1.801
Base of tail height.							
Lateral image.	-	-9.65^{a}	0.38^{b}	12.46^{c}	22.32^{d}	22.56^{d}	-9.614
Trunk depth.							
Lateral image.	-	-6.26^{a}	-0.03^{b}	2.67^{b}	8.38^{c}	12.00^{c}	-3.349
iii Calculated measurements (from direct measurements):							
Shoulder cross-sectional area.							
Live animal	-3.16^{a}	-2.05^{a}	-2.08^{a}	7.30^{b}	4.77^{b}	12.59^{c}	1.140
Shoulder circular dorsal area.							
Dorsal image	1.83^{b}	-4.78^{a}	0.33^{b}	11.30^{c}	23.64^{d}	22.89^{d}	1.307
Hip cross-sectional area.							
Live animal	-5.06^{a}	-7.57^{a}	-4.72^{ab}	-1.70^{bc}	0.21^{c}	5.96^{d}	1.115
Hip circular dorsal area.							
Dorsal image	-1.21^{b}	-6.82^{a}	-2.31^{b}	8.62^{c}	21.14^{d}	23.97^{d}	1.280
Chest cross-sectional area.							
Live animal	-8.60^{b}	-11.44^{a}	-8.18^{b}	-5.65^{c}	-3.55^{c}	-3.54^{c}	0.775
Chest circular dorsal area.							
Dorsal image	-1.40^{a}	-2.80^{a}	1.27^{a}	9.63^{b}	13.17^{bc}	17.72^{c}	1.862
Flank cross-sectional area.							
Live animal	-19.42^{a}	-18.68^{a}	-15.53^{b}	-10.72^{c}	-7.50^{d}	-5.51^{d}	1.022
Flank circular dorsal area.							
Dorsal image	-3.86^{b}	-7.62^{a}	-4.73^{ab}	6.02^{c}	6.17^{c}	11.69^{d}	1.189

Table 5 (cont.)

Body area.							
Live animal.	-3.59^{b}	-7.11^{a}	-5.14^{ab}	-0.24^{c}	1.60^{c}	4.31^{c}	0.727
Dorsal image.	-0.80^{ab}	-3.00^{a}	1.00^{b}	11.51^{c}	25.77^{d}	24.57^{d}	1.297
Chest/flank volume.							
Live animal.	0.83^{a}	0.94^{a}	3.66^{b}	9.39^{c}	9.99^{c}	14.22^{d}	0.702
Body volume							
Live animal.	-15.55^{bc}	-18.68^{a}	-16.62^{ab}	-14.9^{bc}	-13.58^{c}	-14.9^{bc}	0.809
Trunk area							
Dorsal image.	5.19^{b}	0.07^{a}	2.44^{ab}	11.54^{c}	14.68^{d}	18.68^{e}	1.113
Area 1.							
Lateral image.	-	-8.26^{a}	-0.02^{b}	6.71^{c}	13.94^{d}	17.87^{d}	-6.048
Area 2.							
Lateral image.	-	-3.69^{a}	2.84^{b}	4.67^{b}	12.44^{c}	17.37^{d}	-6.724
Area 3.							
Lateral image.	-	-7.94^{a}	0.71^{b}	7.95^{c}	15.58^{d}	19.30^{d}	-7.121
Area 4.							
Lateral image.	-	-3.51^{a}	2.98^{b}	4.55^{b}	12.68^{c}	17.07^{d}	-6.754
Area 5.							
Lateral image.	-	-7.66^{a}	0.34^{b}	7.32^{c}	15.18^{d}	19.17^{d}	-6.871
Area 6.							
Lateral image.	-	-4.07^{a}	2.13^{b}	4.13^{b}	12.35^{c}	18.00^{d}	-6.508

* P-value = 0.001 for all variables

^{abcde} Values with different superscripts within a row indicate effect of weight range in predicted errors.

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

Table 6. Sire line bias (kg) for predicting live weight by fitting the data from the measurements in Study 2 into the prediction equations of Study 1.

	Sire line bias			
Item	Duroc	Landrace	SEM	P-value
Weight, kg.	89.74	91.28	1.303	0.41
Shoulder height.				
Live animal.	3.20	5.02	0.499	0.01
Lateral image.	-2.16	-1.35	0.922	0.54
Body length.				
Live animal.	3.28	1.49	0.468	0.01
Dorsal image.	46.64	44.51	1.212	0.18
Lateral image.	-6.94	-9.54	0.757	0.02
Shoulder width.				
Live animal.	-2.86	-1.60	0.489	0.07
Dorsal image.	-9.78	-8.28	0.851	0.22
Hip width.				
Live animal.	4.17	0.07	0.444	0.001
Dorsal image.	-6.01	-8.79	0.910	0.03
Chest circumference.				
Live animal.	5.48	9.63	0.275	0.001
Flank circumference.				
Live animal.	13.10	15.00	0.333	0.001
ii Additional direct measurements taken on photographs:				
Chest width.				
Dorsal image.	-9.44	-3.38	0.780	0.001
Chest depth.				
Lateral image.	0.38	2.31	0.743	0.07
Flank width.				
Dorsal image.	-2.31	0.64	0.728	0.001
Flank depth.				
Lateral image.	-7.33	-6.05	0.938	0.34
Cross shoulder to hip distance.				
Dorsal image.	-15.00	-16.82	0.956	0.18
Cross chest to flank distance.				
Dorsal image.	-12.71	-13.63	0.887	0.46
Middle back height.				
Lateral image.	-4.92	-3.51	0.848	0.24
Base of tail height.				
Lateral image.	-8.91	-7.95	0.909	0.46
Trunk depth.				
Lateral image.	-2.41	-3.48	0.828	0.36
iii Calculated measurements (from direct measurements):				
Shoulder cross-sectional area.				
Live animal	-2.98	-1.84	0.491	0.1
Shoulder circular dorsal area.				
Dorsal image	-30.24	-28.69	0.864	0.21
Hip cross-sectional area.				
Live animal	3.89	-0.39	0.444	0.001
Hip circular dorsal area.				
Dorsal image	-5.81	-8.77	0.923	0.02
Chest cross-sectional area.				
Live animal	5.01	8.99	0.263	0.001
Chest circular dorsal area.				

Table 6 (cont.)

Dorsal image	-9.29	-3.02	0.795	0.001
Flank cross-sectional area.				
Live animal	12.58	14.34	0.321	0.004
Flank circular dorsal area.				
Dorsal image	-2.22	0.71	0.745	0.01
Body area.				
Live animal.	2.9	0.89	0.302	0.001
Dorsal image.	-10.24	-11.85	0.96	0.24
Chest/flank volume.				
Live animal.	15.55	13.83	0.31	0.001
Body volume				
Live animal.	-1.72	-0.45	0.288	0.001
Trunk area				
Dorsal image.	-9.82	-7.74	0.751	0.05
Area 1.				
Lateral image.	-3.44	-4.88	0.665	0.13
Area 2.				
Lateral image.	-4.69	-6.57	0.646	0.04
Area 3.				
Lateral image.	-4.42	-6	0.671	0.08
Area 4.				
Lateral image.	-4.18	-5.35	0.643	0.2
Area 5.				
Lateral image.	-5.74	-7.09	0.683	0.16
Area 6.				
Lateral image.	-4.87	-7.08	0.673	0.02

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

APPENDIX A

Descriptive statistics for live weight and measurements from Study 1 and 2

Table 7. Descriptive statistics of live weight and measurements taken directly from the animal and on dorsal and lateral photographic images for the overall Study I period.

Measurement	N	Mean	Std Dev	Minimum	Maximum
Weight, kg	420	94.8	26.05	36.8	142.8
i. Live animal measurements taken on the live animal and/or the photographs:					
Shoulder height.					
Live animal	414	54.4	5.35	40.0	68.0
Lateral image	327	52.8	5.11	30.4	76
Body length.					
Live animal, kg.	414	84.6	7.65	64.0	99.0
Dorsal image	419	65.8	6.54	43.6	79.1
Lateral image	325	68.6	5.33	50.6	81.4
Shoulder width, cm					
Live animal	414	30.7	3.37	22.0	38.5
Dorsal image	420	28.4	2.94	19.0	35.8
Hip width, cm					
Live animal	414	29.3	3.07	22.0	36
Dorsal image	420	27.7	2.56	21.1	35
Chest circumference, cm					
Live animal	414	101.6	10.34	74.0	122
Flank circumference, cm					
Live animal	414	102.8	9.06	74.0	121
ii Additional direct measurements taken on photographs:					
Chest width, cm.					
Dorsal image	419	25.4	3.04	17.8	31.6
Chest depth, cm.					
Lateral image	327	32.4	3.37	24.1	41.6
Flank width, cm.					
Dorsal image	419	23.7	2.78	16.4	29.8
Flank depth, cm.					
Lateral image	327	35.2	3.60	26.0	43.1
Cross shoulder to hip distance, cm.					
Dorsal image	420	56.1	6.01	39.6	69.5
Cross chest to flank distance, cm.					
Dorsal image	419	40.0	4.45	29.1	50.2
Middle back height, cm.					
Lateral image	327	59.7	5.15	36.7	74.7
Base of tail height, cm					
Lateral image	326	50.8	4.13	38.1	62.4
Trunk depth, cm.					
Lateral image	326	38.5	3.37	30.3	48.6
iii Calculated measurements (from direct measurements):					
Shoulder cross-sectional area, cm2					
Live animal	414	750.4	161.16	380.1	1164.2
Shoulder circular dorsal area, cm2.					
Dorsal image	420	44.6	4.62	29.8	56.2
Hip cross-sectional area, cm2.					
Live animal	414	682.0	139.54	380.1	1017.9
Hip circular dorsal area, cm2.					
Dorsal image	420	43.5	4.02	33.2	55
Chest cross-sectional area, cm2.					
Live animal	414	830.3	164.73	435.8	1184.4
Chest circular dorsal area, cm2.					
Dorsal image	419	39.8	4.77	28.0	49.7

Table 7 (cont.)

Flank cross-sectional area, cm2.					
Live animal	414	848.2	146.17	435.8	1165.1
Flank circular dorsal area, cm2.					
Dorsal image	419	37.3	4.37	25.8	46.8
Body area, cm^2					
Live animal	414	2558.5	466.82	1408	3456
Dorsal image	419	2919.2	519.73	1692.7	4154.2
Chest/flank volume, cm^3					
Live animal	414	61.5	16.91	24.3	100.4
Body volume, cm^3					
Live animal	414	72.0	18.54	27.9	107.9
Trunk area, cm^2					
Dorsal image	417	2558.5	492.59	1417.7	3618.8
Area 1, cm^2					
Lateral image	324	3743.1	501.23	2635.0	5337.1
Area 2, cm^2					
Lateral image	324	2432.3	363.66	1596.4	3429.7
Area 3, cm^2					
Lateral image	324	3560.9	475.45	2497.1	4989.8
Area 4, cm^2					
Lateral image	324	2323.9	356.05	1520.4	3308.9
Area 5, cm^2					
Lateral image	324	3801.5	511.78	2596.5	5514.9
Area 6, cm^2					
Lateral image	324	2534.7	383.08	1624.3	3573.5

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

Table 8. Descriptive statistics of live weight and measurements taken directly from the animal and on dorsal and lateral photographic images for the overall Study II period.

Measurement	N	Mean	Std Dev	Minimum	Maximum
Weight, kg	838	90.1	26.23	39	147.5
i. Live animal measurements taken on the live animal and/or the photographs:					
Shoulder height.					
Live animal	820	52.6	5.46	38.0	64.0
Lateral image	802	49.0	5.58	33.2	64.9
Body length.					
Live animal, kg.	820	82.4	8.68	62.0	103.0
Dorsal image	838	68.3	5.69	52.0	87.8
Lateral image	803	68.0	7.94	48.3	93.8
Shoulder width, cm					
Live animal	820	30.5	3.49	22.0	38.0
Dorsal image	838	29.0	2.75	21.5	36.7
Hip width, cm					
Live animal	820	28.5	3.10	20.0	35.0
Dorsal image	838	28.0	2.34	20.0	35.0
Chest circumference, cm					
Live animal	820	96.9	11.06	72.0	121.0
Flank circumference, cm					
Live animal	820	96.1	10.27	71.0	119.0
ii Additional direct measurements taken on photographs:					
Chest width, cm.					
Dorsal image	838	25.6	2.70	18.8	33.9
Chest depth, cm.					
Lateral image	799	30.0	3.78	20.7	41.4
Flank width, cm.					
Dorsal image	838	23.3	2.62	16.0	32.2
Flank depth, cm.					
Lateral image	801	34.4	4.35	22.9	49.2
Cross shoulder to hip distance, cm.					
Dorsal image	837	59.3	5.31	43.5	77.5
Cross chest to flank distance, cm.					
Dorsal image	836	41.8	4.13	30.5	53.0
Middle back height, cm.					
Lateral image	803	57.6	6.40	38.3	77.8
Base of tail height, cm					
Lateral image	802	50.3	5.89	34.2	71.0
Trunk depth, cm.					
Lateral image	802	37.1	4.05	27.2	51.5
iii Calculated measurements (from direct measurements):					
Shoulder cross-sectional area, cm2					
Live animal	820	738.7	166.01	380.1	1134.1
Shoulder circular dorsal area, cm2.					
Dorsal image	838	45.6	4.32	33.7	57.7
Hip cross-sectional area, cm2.					
Live animal	820	644.6	137.81	314.2	962.1
Hip circular dorsal area, cm2.					
Dorsal image	838	44.0	3.67	31.4	55.0
Chest cross-sectional area, cm2.					
Live animal	820	757.4	169.66	412.5	1165.1

Table 8 (cont.)

Chest circular dorsal area, cm2.					
Dorsal image	838	40.2	4.24	29.5	53.3
Flank cross-sectional area, cm2.					
Live animal	820	743.0	156.88	401.1	1126.9
Flank circular dorsal area, cm2.					
Dorsal image	838	36.6	4.11	25.2	50.6
Body area, cm^2					
Live animal	820	2453.4	503.34	1408.0	3708.0
Dorsal image	838	3076.2	488.18	1858.7	4648.1
Chest/flank volume, cm^3					
Live animal	820	58.1	17.74	24.4	105.2
Body volume, cm^3					
Live animal	820	63.1	19.49	25.9	109.3
Trunk area, cm^2					
Dorsal image	836	1616.8	310.84	933.2	2570.8
Area 1, cm^2					
Lateral image	801	3595.0	768.88	1973.0	6071.2
Area 2, cm^2					
Lateral image	796	2325.7	515.33	1267.9	4209.6
Area 3, cm^2					
Lateral image	801	3414.5	734.82	1877.7	5984.2
Area 4, cm^2					
Lateral image	797	2216.6	504.70	1188.6	4063.7
Area 5, cm^2					
Lateral image	802	3707.8	797.52	2091.3	6271.9
Area 6, cm^2					
Lateral image	800	2456.9	541.88	1326.4	4438.8

Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length

APPENDIX B

Regression equations for predicting live weight from Study 1 and 2.

Table 9. Regression equations for predicting live weight from Study 1

Direct measurements on live animals, cm

Number of variables in model	Intercept	Chest circumference	Flank circumference	Hip width	Body length	Shoulder width	Shoulder height	R^2	RSD
1	-153.740	2.445						0.93	7.1
1	-180.090		2.672					0.85	10.1
1	-136.640			7.893				0.85	10.1
1	-150.170						4.499	0.84	10.5
1	-123.172					7.090		0.83	10.8
1	-167.245				3.098			0.82	11.2
2	-165.253	1.772					1.467	0.95	6.1
2	-158.107	1.806		2.363				0.94	6.5
2	-166.151	1.966			0.722			0.94	6.7
2	-154.883	1.946				1.686		0.93	6.7
3	-167.169	1.358		1.857			1.276	0.95	5.7
3	-165.621	1.389				1.414	1.392	0.95	5.8
3	-168.827	1.663			0.292		1.284	0.95	6.1
3	-166.427	1.717	0.068				1.462	0.95	6.1
4	-166.984	1.220		1.421		0.859	1.280	0.96	5.6
4	-170.235	1.271		1.823	0.253		1.121	0.95	5.6
4	-166.325	1.395	-0.050	1.872			1.278	0.95	5.7
4	-169.391	1.267			0.309	1.439	1.194	0.95	5.7
5	-165.870	1.268	-0.066	1.438		0.863	1.283	0.96	5.6
5	-169.146	1.318	-0.067	1.843	0.256		1.122	0.95	5.6
5	-168.957	1.287	-0.026		0.310	1.444	1.195	0.95	5.7
5	-167.028	1.346	-0.074	1.638	0.635	1.006		0.95	6.0
6	-168.852	1.181	-0.085	1.383	0.275	0.909	1.113	0.96	5.5

Calculated measurements on live animals, cm^2

Number of variables in model	Intercept	Body area	Chest cross-sectional area	Flank cross-sectional area	Hip cross-sectional area	Shoulder cross-sectional area	R^2	RSD
1	-43.965	0.054					0.93	7.0
1	-32.852		0.154				0.93	7.0
1	-46.116			0.166			0.86	9.9
1	-23.657				0.174		0.85	10.1
1	-16.308					0.148	0.82	11.0
2	-42.026	0.028	0.079				0.95	5.6
2	-35.304		0.113		0.053		0.94	6.2
2	-48.979	0.041		0.045			0.94	6.5
2	-33.515		0.123			0.035	0.94	6.6
3	-41.507	0.024	0.078		0.013		0.95	5.6
3	-41.467	0.028	0.082	-0.004			0.95	5.6
3	-41.984	0.028	0.079			0.001	0.95	5.6
3	-35.218		0.104		0.043	0.019	0.95	6.1
4	-40.815	0.025	0.082	-0.005	0.013		0.95	5.6
4	-41.536	0.025	0.078		0.013	0.000	0.95	5.6
4	-41.425	0.028	0.082	-0.004		0.001	0.95	5.6
4	-35.182		0.104	0.000	0.043	0.019	0.95	6.2
5	-40.845	0.025	0.082	-0.005	0.014	0.000	0.95	5.6

Table 9 (cont.)

Calculated measurements on live animals, m^3

Number of variables in model	Intercept	Body volume	Chest/ flank volume	R^2	RSD
1	-3.820		1.369	0.93	6.7
1	2.719	1.496		0.93	7.0
2	-2.772	0.710	0.747	0.95	5.9

Direct measurements on dorsal images, cm

Number of variables in model	Intercept	Body length	Shoulder width	Hip width	Chest width	Flank width	Cross shoulder to hip	Cross chest to flank	R^2	RSD
1	-102.801					8.331			0.79	12.0
1	-96.505				7.546				0.78	12.3
1	-99.615							4.856	0.69	14.6
1	-108.860		7.170						0.65	15.3
1	-131.542			8.168					0.64	15.5
1	-96.427						3.410		0.62	16.1
1	-78.328	2.630							0.44	19.6
2	-108.606				3.646	4.679			0.82	11.1
2	-118.135					6.006		1.760	0.82	11.1
2	-120.513					6.521	1.081		0.81	11.3
2	-115.072				5.274			1.903	0.81	11.3
2	-116.842		1.908			6.638			0.80	11.6
3	-119.271				2.873	3.645		1.369	0.83	10.6
3	-120.043				2.875	4.151	0.776		0.83	10.8
3	-124.553		1.144			5.294		1.531	0.82	11.0
3	-116.487	0.282			3.485	4.401			0.82	11.1
3	-121.023					5.932	0.450	1.246	0.82	11.1
4	-115.302	-0.224			2.837	3.711		1.622	0.83	10.6
4	-115.718			-0.488	2.976	3.855		1.428	0.83	10.6
4	-116.940		-0.439		3.222	3.631		1.409	0.83	10.6
4	-120.532				2.797	3.674	0.202	1.148	0.83	10.6
4	-114.364			-0.924	3.004	4.545	0.906		0.83	10.7
5	-115.631	-0.368			2.638	3.811	0.470	1.275	0.83	10.6
5	-115.937			-0.744	2.904	4.014	0.334	1.094	0.83	10.6
5	-114.155	-0.202	-0.289		3.070	3.696		1.624	0.83	10.6
5	-113.912	-0.194		-0.264	2.897	3.818		1.620	0.83	10.6
5	-117.874		-0.592		3.238	3.666	0.280	1.118	0.83	10.6
6	-112.951	-0.330		-0.518	2.729	4.034	0.534	1.224	0.83	10.6
6	-113.823	-0.348	-0.464		2.993	3.798	0.516	1.245	0.83	10.6
6	-115.441		-0.338	-0.579	3.132	3.934	0.349	1.089	0.83	10.6
6	-113.620	-0.190	-0.221	-0.153	3.050	3.762		1.622	0.83	10.6
6	-111.969	-0.203	-0.366	-0.616	3.144	4.523	1.081		0.83	10.8
7	-112.520	-0.327	-0.310	-0.368	2.940	3.961	0.546	1.218	0.83	10.6

Table 9 (cont.)

Calculated measurements on dorsal images, cm^2

Number of variables in model	Intercept	Shoulder circular dorsal area	Hip circular dorsal area	Chest circular dorsal area	Flank circular dorsal area	Body area	Trunk area	R^2	RSD
1	-102.710				5.302			0.79	12.0
1	-96.510			4.804				0.78	12.3
1	-21.530						0.045	0.74	13.2
1	-108.720	4.563						0.65	15.3
1	-131.510		5.200					0.64	15.5
1	-21.379					0.040		0.63	15.8
2	-108.570			2.320	2.979			0.82	11.1
2	-82.410				3.666		0.016	0.80	11.6
2	-116.690	1.209			4.229			0.80	11.6
2	-96.150				4.409	0.009		0.80	11.7
2	-74.790			3.065			0.019	0.80	11.7
3	-98.100			1.973	2.546		0.008	0.82	11.1
3	-105.070			2.096	2.791	0.004		0.82	11.1
3	-110.230		0.128	2.285	2.912			0.82	11.1
3	-108.990	0.045		2.282	2.977			0.82	11.1
3	-97.380	0.777			3.453		0.011	0.81	11.5
4	-94.020		-0.214	1.991	2.603		0.009	0.82	11.1
4	-94.620			1.938	2.438	-0.003	0.012	0.82	11.1
4	-95.780	-0.171		2.096	2.523		0.008	0.82	11.1
4	-96.040		-0.525	2.117	2.943	0.007		0.82	11.1
4	-99.230	-0.448		2.385	2.720	0.006		0.82	11.1
5	-93.120	-0.353	-0.427	2.341	2.858	0.008		0.82	11.1
5	-93.660	-0.097	-0.164	2.056	2.577		0.009	0.82	11.1
5	-93.940		-0.164	1.977	2.558	-0.001	0.010	0.82	11.1
5	-94.730	-0.043		1.975	2.453	-0.003	0.011	0.82	11.1
5	-95.120	1.662	1.473		0.802	-0.050	0.066	0.82	11.1
6	-92.505	-1.148	-1.224	3.241	3.756	0.032	-0.027	0.82	11.1

Direct measurements on lateral images, cm

Number of variables in model	Intercept	Body length	Shoulder height	Middle back height	Base of tail height	Chest depth	Trunk depth	Flank depth	R^2	RSD
1	-86.480						4.859		0.60	13.3
1	-57.490							4.500	0.59	13.5
1	-50.720					4.677			0.56	14.0
1	-71.280	2.506							0.40	16.4
1	-48.260			2.494					0.37	16.8
1	-10.261		2.103						0.26	18.2
1	-23.319				2.441				0.22	18.6
2	-81.570					2.573		2.815	0.67	12.0
2	-116.900	1.389				3.779			0.67	12.1
2	-125.230	1.017					4.057		0.66	12.2
2	-86.290						2.796	2.255	0.64	12.7
2	-85.580					2.033	3.126		0.63	12.9
3	-115.330	0.859				2.654		2.027	0.72	11.2
3	-126.220	1.073				2.231	2.107		0.70	11.6
3	-70.980		0.702			3.456		2.753	0.68	11.9
3	-70.550			-0.698		3.145		3.160	0.68	11.9
3	-85.260					2.289	0.649	2.469	0.68	12.0
4	-104.830	0.885		-0.718		3.228		2.367	0.73	11.0
4	-105.910	0.856	-0.597			3.393		1.981	0.73	11.1
4	-110.140	0.959			-0.355	2.796		2.067	0.72	11.2

Table 9 (cont.)

4	-118.050	0.840				2.377	0.570	1.772	0.72	11.2
4	-117.870	1.096		-0.809		2.560	2.828		0.71	11.4
5	-108.270	0.850		-0.898		2.752	1.276	1.881	0.73	10.9
5	-101.570	0.877	-0.366	-0.546		3.543		2.258	0.73	11.0
5	-103.520	0.943		-0.650	-0.183	3.238		2.362	0.73	11.0
5	-103.200	0.934	-0.552		-0.255	3.431		2.018	0.73	11.0
5	-108.670	0.836	-0.600			3.111	0.588	1.718	0.73	11.1
6	-105.440	0.847	-0.286	-0.749		3.039	1.167	1.837	0.73	10.9
6	-108.300	0.886		-0.859	-0.077	2.748	1.243	1.897	0.73	10.9
6	-100.620	0.930	-0.364	-0.486	-0.161	3.544		2.255	0.73	11.0
6	-106.140	0.911	-0.560		-0.231	3.163	0.546	1.772	0.73	11.0
6	-114.980	1.095	-0.408	-0.597	0.022	2.929	2.646		0.71	11.4
7	-105.567	0.881	-0.293	-0.709	-0.068	3.037	1.137	1.851	0.73	10.9

Calculated measurements on lateral images, cm^2 [a]

Number of variables in model	Intercept	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	R^2	RSD
1	-13.126				0.049			0.68	12.0
1	-15.374		0.048					0.67	12.2
1	-11.528						0.044	0.64	12.7
1	-12.747	0.030						0.51	14.8
1	-10.214					0.029		0.50	15.0
1	-9.695			0.031				0.48	15.2
2	-1.275				0.071	-0.017		0.70	11.6
2	-1.403	-0.017			0.071			0.70	11.7
2	-4.608		0.070			-0.017		0.69	11.7
2	-3.180			-0.013	0.065			0.69	11.8
2	-5.148	-0.017	0.070					0.69	11.8
3	-2.715	-0.022	0.141				-0.063	0.71	11.5
3	-4.363		0.120			-0.018	-0.047	0.70	11.5
3	0.656	-0.018			0.097		-0.024	0.70	11.6
3	-4.150		0.136	-0.017			-0.065	0.70	11.6
3	-0.530				0.087	-0.016	-0.016	0.70	11.6
4	-1.027	-0.021	0.098		0.037		-0.056	0.71	11.4
4	-3.102	-0.031	0.139	0.009			-0.060	0.71	11.5
4	-2.698	-0.019	0.140			-0.002	-0.061	0.71	11.5
4	-2.605		0.076		0.038	-0.018	-0.040	0.71	11.5
4	-1.553		0.082	-0.018	0.048		-0.057	0.70	11.5
5	-1.411	-0.027	0.100	0.006	0.034		-0.055	0.71	11.4
5	-1.010	-0.019	0.096		0.037	-0.002	-0.054	0.71	11.4
5	-3.094	-0.031	0.139	0.009		0.000	-0.059	0.71	11.5
5	-1.189		0.082	-0.008	0.042	-0.011	-0.048	0.71	11.5
5	0.676	-0.009		-0.001	0.094	-0.008	-0.020	0.70	11.6
6	-1.379	-0.026	0.099	0.005	0.034	-0.001	-0.054	0.71	11.5

Area 1 = ((shoulder height + back height +base of tail height)/3) x length ; area 2 =((Chest depth + middle depth + flank depth)/3 x length); area 3 = ((shoulder height + tail height)/2) x length; area 4 = ((chest depth + flank depth)/2) x length; area 5 = ((back height + tail height)/2) x length; area 6 = ((mid depth + flank depth)/2) x length

Table 10 . Regression equations for predicting live weight for Study 2

Direct measurements on live animals, cm

Number of variables in model	Intercept	Chest circumference	Flank circumference	Hip width	Body length	Shoulder width	Shoulder height	R^2	RSD
1	-133.647	2.313						0.95	5.7
1	-146.958		2.472					0.94	6.5
1	-135.521			7.937				0.88	9.1
1	-142.631				2.829			0.88	9.2
1	-121.727					6.966		0.86	9.9
1	-142.749						4.435	0.85	10.0
2	-145.665	1.681			0.889			0.97	4.7
2	-142.378	1.708		2.364				0.97	4.9
2	-156.515		1.686		1.032			0.96	5.3
2	-142.592	1.867					0.991	0.96	5.3
2	-141.080	1.513	0.884					0.96	5.3
3	-149.872	1.351		1.770	0.716			0.97	4.2
3	-147.655	1.387			0.829	1.162		0.97	4.4
3	-149.959	1.161	0.635		0.811			0.97	4.5
3	-149.108	1.387		2.163			0.828	0.97	4.5
3	-148.935	1.522			0.770		0.541	0.97	4.6
4	-152.975	0.961	0.508	1.630	0.668			0.98	4.0
4	-152.840	1.209		1.737	0.609		0.504	0.98	4.1
4	-150.201	1.254		1.478	0.714	0.597		0.98	4.1
4	-151.308	0.949	0.566		0.766	1.060		0.97	4.2
4	-151.618	1.178			0.686	1.263	0.627	0.97	4.2
5	-155.262	0.877	0.456	1.615	0.578		0.442	0.98	3.9
5	-153.576	1.076		1.379	0.594	0.726	0.561	0.98	4.0
5	-153.187	0.883	0.493	1.364	0.668	0.552		0.98	4.0
5	-154.318	0.822	0.493		0.648	1.162	0.551	0.98	4.1
5	-152.873	0.864	0.510	1.625		0.746	0.792	0.97	4.3
6	-155.810	0.772	0.431	1.290	0.566	0.672	0.499	0.98	3.8

Calculated measurements on live animals, cm^2

Number of variables in model	Intercept	Body area	Chest cross-sectional area	Flank cross-sectional area	Hip cross-sectional area	Shoulder cross-sectional area	R^2	RSD
1	-23.743		0.151				0.95	5.6
1	-33.927	0.051					0.95	5.9
1	-29.604			0.162			0.94	6.6
1	-24.332				0.178		0.88	9.2
1	-17.475					0.146	0.86	9.9
2	-31.873	0.025	0.081				0.98	3.9
2	-35.767	0.029		0.075			0.97	4.4
2	-28.492		0.110		0.055		0.97	4.7
2	-25.667		0.122			0.032	0.96	5.2
3	-33.130	0.023	0.059	0.029			0.98	3.8
3	-31.950	0.022	0.080		0.013		0.98	3.9
3	-32.004	0.027	0.082			-0.007	0.98	3.9
3	-35.812	0.026		0.074	0.013		0.97	4.3
4	-33.179	0.020	0.059	0.028	0.012		0.98	3.8
4	-33.247	0.025	0.061	0.029		-0.006	0.98	3.8
4	-32.097	0.023	0.082		0.014	-0.007	0.98	3.9
4	-35.845	0.026		0.074	0.013	-0.001	0.97	4.3
5	-33.310	0.022	0.061	0.028	0.013	-0.007	0.98	3.8

Table 10 (cont.)

Calculated measurements on live animals, m^3

Number of variables in model	Intercept	Body volume	Chest/flank volume	R^2	RSD
1	7.112		1.322	0.97	4.8
1	7.086	1.436		0.94	6.2
2	5.883	0.475	0.904	0.97	4.3

Direct measurements on dorsal images, cm

Number of variables in model	Intercept	Body length	Shoulder width	Hip width	Chest width	Flank width	Cross shoulder to hip	Cross chest to flank	R^2	RSD
1	-101.819					8.246			0.68	14.9
1	-105.684				7.641				0.62	16.2
1	-117.446		7.152						0.56	17.3
1	-103.038							4.624	0.53	18.0
1	-131.711			7.915					0.50	18.6
1	-106.752						3.318		0.45	19.5
1	-71.993	2.372							0.26	22.5
2	-121.244					6.497		1.439	0.70	14.4
2	-120.284					7.151	0.741		0.69	14.7
2	-110.593				2.269	6.124			0.69	14.7
2	-111.881		1.306			7.049			0.68	14.8
2	-95.459			-0.644		8.748			0.68	14.9
3	-95.065	-1.254				6.521		2.850	0.72	13.9
3	-100.955	-1.573				7.119	2.239		0.71	14.1
3	-105.570			-1.989		7.688		1.735	0.70	14.3
3	-123.835				1.338	5.480		1.248	0.70	14.4
3	-124.953		0.632			6.024		1.353	0.70	14.4
4	-100.628	-1.391	1.434			5.449		2.808	0.73	13.7
4	-97.419	-1.630				6.445	1.083	2.024	0.73	13.7
4	-97.542	-1.272			1.473	5.401		2.659	0.72	13.8
4	-93.955	-1.214		-0.245		6.667		2.842	0.72	13.9
4	-103.220	-1.562			1.622	5.848	2.062		0.72	14.0
5	-101.589	-1.675	1.185			5.573	0.887	2.139	0.73	13.7
5	-99.481	-1.618			1.331	5.439	1.002	1.913	0.73	13.7
5	-96.668	-1.237	1.762	-1.155		5.892		2.761	0.73	13.7
5	-94.140	-1.544		-0.778		6.901	1.196	1.913	0.73	13.7
5	-100.384	-1.364	1.058		0.723	5.180		2.725	0.73	13.7
6	-96.538	-1.521	1.574	-1.522		6.179	1.043	1.960	0.73	13.6
6	-95.329	-1.503		-1.031	1.458	5.947	1.143	1.756	0.73	13.7
6	-101.340	-1.651	0.759		0.807	5.277	0.908	2.030	0.73	13.7
6	-96.656	-1.221	1.423	-1.097	0.621	5.639		2.693	0.73	13.7
6	-96.708	-1.380	0.768	-1.984	1.309	6.625	2.135		0.72	13.9
7	-96.523	-1.508	1.198	-1.463	0.683	5.904	1.055	1.875	0.73	13.6

Calculated measurements on dorsal images, cm^2

Number of variables in model	Intercept	Shoulder circular dorsal area	Hip circular dorsal area	Chest circular dorsal area	Flank circular dorsal area	Body area	Trunk area	R^2	RSD
1	-101.798				5.249			0.68	14.9
1	-21.018						0.069	0.66	15.3
1	-105.848			4.868				0.62	16.2
1	-117.366	4.551						0.56	17.4

Table 10 (cont.)

1	-132.059		5.047						0.50	18.6
1	-20.668					0.036			0.45	19.5
2	-73.716				3.140		0.030		0.70	14.5
2	-110.632			1.452	3.892				0.69	14.7
2	-5.928					-0.019	0.096		0.68	14.8
2	-111.771	0.824			4.494				0.68	14.8
2	-95.657		-0.396		5.557				0.68	14.9
3	-56.970				2.958	-0.018	0.058		0.72	14.0
3	-54.932	2.199				-0.029	0.083		0.71	14.2
3	-46.118		-1.332		3.658		0.038		0.70	14.3
3	-79.408			0.395	3.018		0.027		0.70	14.5
3	-57.158		2.234			-0.032	0.091		0.70	14.5
4	-77.880	1.415			2.342	-0.024	0.057		0.72	13.8
4	-65.199		0.542		2.714	-0.021	0.059		0.72	14.0
4	-62.691			0.397	2.835	-0.018	0.054		0.72	14.0
4	-84.988	1.903	1.598			-0.037	0.081		0.71	14.1
4	-50.583	2.513		-0.574		-0.030	0.088		0.71	14.2
5	-71.854	1.878		-0.892	2.417	-0.026	0.065		0.72	13.8
5	-84.006	1.398	0.420		2.161	-0.026	0.058		0.72	13.8
5	-70.136		0.514	0.373	2.612	-0.021	0.056		0.72	14.0
5	-80.500	2.285	1.648	-0.717		-0.039	0.087		0.71	14.1
5	-52.800	0.696	-1.650	-0.004	3.514		0.034		0.70	14.3
6	-78.304	1.866	0.449	-0.906	2.225	-0.029	0.066		0.72	13.8

Direct measurements on lateral images, cm

Number of variables in model	Intercept	Body length	Shoulder height	Middle back height	Base of tail height	Chest depth	Trunk depth	Flank depth	R^2	RSD
1	-88.945					5.992			0.77	12.4
1	-98.595	2.782							0.73	13.3
1	-81.760							5.006	0.72	13.7
1	-107.779						5.352		0.71	13.9
1	-92.104		3.730						0.65	15.2
1	-96.805			3.257					0.65	15.2
1	-84.363				3.477				0.63	15.7
2	-113.204	1.389				3.649			0.84	10.5
2	-99.238					3.878		2.138	0.80	11.4
2	-106.735				1.256	4.476			0.80	11.5
2	-110.160	1.606				2.658			0.80	11.4
2	-123.493	1.653					2.743		0.80	11.6
3	-115.190	1.165				2.839		1.205	0.84	10.2
3	-119.961	1.223				3.013	1.001		0.84	10.3
3	-117.587	1.186			0.560	3.316			0.84	10.3
3	-116.236	1.322		0.292		3.341			0.84	10.4
3	-113.389	1.384	0.043			3.598			0.84	10.4
4	-118.272	1.031			0.431	2.667		1.079	0.85	10.1
4	-117.450	1.137				2.754	0.353	1.020	0.84	10.2
4	-114.482	1.173		-0.077		2.885		1.257	0.84	10.2
4	-114.742	1.174	-0.032			2.896		1.170	0.84	10.1
4	-123.493	1.050			0.513	2.755	0.926		0.84	10.2
5	-116.312	1.034		-0.281	0.516	2.803		1.242	0.85	10.1
5	-120.706	1.000			0.435	2.571	0.381	0.878	0.85	10.1
5	-116.987	1.047	-0.145		0.436	2.846		1.054	0.85	10.0
5	-122.714	1.045		-0.287	0.611	2.856	1.145		0.84	10.2
5	-116.499	1.148		-0.156		2.822	0.441	1.080	0.84	10.2
6	-119.225	0.988		-0.408	0.563	2.694	0.620	0.991	0.85	10.0
6	-115.681	1.046	-0.026	-0.299	0.508	2.869		1.223	0.85	10.0
6	-119.279	1.020	-0.110		0.434	2.734	0.314	0.888	0.85	10.0
6	-122.737	1.053	0.110	-0.349	0.596	2.800	1.150		0.85	10.1

Table 10 (cont.)

6	-116.646	1.151	0.121	-0.231		2.755	0.454	1.075	0.85	10.1
7	-119.174	0.996	0.097	-0.465	0.548	2.651	0.621	0.989	0.85	10.0
Calculated measurements on lateral images, cm[2 a]										
Number of variables in model	Intercept	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6		R^2	RSD
1	-12.096				0.046				0.83	10.7
1	-14.589		0.045						0.82	10.9
1	-13.840						0.043		0.80	11.4
1	-16.561	0.030							0.79	11.7
1	-15.704			0.031					0.79	11.8
1	-15.291					0.029			0.78	12.0
2	-13.388		0.106				-0.058		0.83	10.6
2	-10.816				0.062		-0.015		0.83	10.7
2	-13.152			0.004	0.040				0.83	10.7
2	-12.418	0.002			0.044				0.83	10.7
2	-12.003		-0.004		0.050				0.83	10.7
3	-12.506		0.076		0.021		-0.049		0.83	10.6
3	-13.664		0.102	0.002			-0.057		0.83	10.6
3	-13.530		0.105			0.001	-0.058		0.83	10.6
3	-13.109	0.000	0.108				-0.060		0.83	10.6
3	-12.040	-0.020		0.022	0.046				0.83	10.6
4	-13.175	-0.020	0.101	0.019			-0.051		0.83	10.5
4	-12.664		0.073	0.002	0.021		-0.049		0.83	10.5
4	-12.624		0.075		0.021	0.001	-0.049		0.83	10.6
4	-12.115	0.000	0.077		0.022		-0.051		0.83	10.6
4	-13.688		0.098	0.006		-0.005	-0.052		0.83	10.6
5	-12.803	-0.033	0.109	0.021		0.010	-0.057		0.83	10.5
5	-12.427	-0.019	0.078	0.018	0.016		-0.045		0.83	10.5
5	-11.778	-0.008	0.082		0.023	0.007	-0.056		0.83	10.5
5	-12.761		0.072	0.005	0.019	-0.004	-0.045		0.83	10.5
5	-11.081	-0.023		0.018	0.059	0.005	-0.012		0.83	10.6
6	-11.964	-0.033	0.085	0.020	0.018	0.011	-0.051		0.83	10.5

[a]Area 1 = ((shoulder height + back height +base of tail height)/3) x body length ; area 2 =((Chest depth + middle depth + flank depth)/3 x body length); area 3 = ((shoulder height + tail height)/2) x body length; area 4 = ((chest depth + flank depth)/2) x body length; area 5 = ((back height + tail height)/2) x body length; area 6 = ((mid depth + flank depth)/2) x body length.