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Modeling of pig growth by S-function – least absolute deviation approach for parameter estimation

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Abstract

The aim of this study was to determine a mathematical model which can be used to describe the growth of the pig. The study was conducted on 60 pigs (30 barrows and 30 gilts) in the interval between the age of 49 and 215 days. All animals were weighed at 49th day after birth. For the purpose of growth measurements pigs were weighted every 7th day during the experiment. Every 21th day four pigs were selected for the slaughter according to average live weight. By applying the generalised logistic function, the growth of live weight and tissues were described. Thereby optimal parameters in the model were estimated on the basis of measurement data by means of the robust least absolute deviations principle. The prediction of optimum slaughter age/weight, on the basis of such model represent a contribution of this paper to the practice.

Keywords: asymmetric S-function, pigs, growth, prediction, body weight, tissue

Introduction

The pork industry pays for a meat unit exclusively, it is desirable to know until what age/body weight it is rational to fatten an animal. Traditionally, the changes of body composition during growth are studied using the methods such as dissection of the carcass, computed tomography, magnetic resonance imaging and some other useful techniques at varying age or body weight (Giles *et al.* 2009). It is a complex problem, especially when it comes to a modelling of the growth patterns. In the depiction of animal growth as the function of time different curves, esspecially from the family of exponential curves, have been used. Indeed, there are many mathematical models succesfully used for analysis and accurate prediction of the animal growth like logistic (Jukić & Scitovski 2003), von Bertalanfy (Köhn *et al.* 2007), Gompertz (Vouri *et al.* 2006), and various forms of generalised logistic functions (López *et al.* 2000, Scitovski *et al.* 2006). If some of the dynamic, non-linear functions are selected for modelling, it is important to correctly determine the upper limit of growth, i.e. biological maximum (A) growth of an animal, mature weight or a maximum weight in the point of interest. To obtain the accurate estimations of the final size, it is required that the animals are kept alive beyond a typical market weight which is not a common practice in the case of meat animals. For that reason, in some investigations of pig growth which is based on the maximum growth capacity the final weight is determined experimentally. For example, Davies & Kallweit (1979) established final weight of German Landrace pigs at 200 kg; Walstra (1980) reported final weight of Danish Landrace between 300 and 350 kg; Solanes & Stern (2001) found this weight to be between 258.4 and 284.8 kg for Large White. Obviously, this trait is influenced by breed and sex. On the other hand, other authors used predetermined final weight chosen on the empirical knowledge (Kralik *et al.* 1999, Jelen 1998) or on the combination of empirical knowledge and goodness of fit analysis (Kušec *et al.* 2007). These authors used asymmetric S-function in their investigations of the pig growth up to 120 kg live weight setting the biological maximum growth to 220 kg. Similarly the coefficient of asymmetry was empirically set to 0.01. Subsequently, Kušec *et al.* (2008) showed that asymmetric S-function can be used as a tool in the prediction of live weight, muscle and fat growth of pigs not only within the interval of measurement but throughout the whole time scale. They were able to perform the predictions for individual animal as well as for the group of animals on the basis of the first weighing. In mathematical modelling, one of the frequently occurring problems is to evaluate many parameters simultaneously. Parameters of the growth function are most often estimated on the basis of measurement data by applying the least squares principle (Kušec *et al.* 2007, Köhn *et al.* 2007). These nonlinear optimisation problems very often refer to a numerically very demanding and unstable process. Moreover, in practice it is also possible that among the data there might appear severe measurement errors or poor measurement samples known as oultliers. The asymmetric S-function is a good example of the over-determined model where it is difficult to identify all the parameters in every case. For this reason many researchers have chosen to select some parameters on the empirical basis. Having this in mind, the main objective of this paper is to establish a new approach to the modelling of pig growth by asymmetric S-function where the optimal parameters in the model will be estimated on the basis of measurement data by means of the robust least absolute deviations principle.

Material and methods

The study was carried out on 60 pigs (30 barrows and 30 gilts) during the time interval between 49 and 215 days of age. The pigs were 3 way crossbreds, representing the standard fattening pig type of Batalle breeding programme. First day after farrowing, the piglets were properly marked. Four offspring from one sow (2 barrows and 2 gilts) were selected to enter in the experiment, 15 individuals each. The selected piglets were healthy, with good exterior appearance and appropriately developed body. All animals were weighed at 49th day after birth; subsequently, the pigs were weighted every 7th day during the experiment. Every 21th day 4 pigs were selected for the slaughter according to average live weight. Total dissections of main tissues (muscle, fat and bone) were determined according to Weniger *et al.* (1963) on the right side of the carcass. During the experiment 3 female animals were excluded due to disease and death. The animals were kept in the same housing and feeding conditions. The pigs were fed *ad libitum*. The diet provided until 25 kg average live weight consisted of 13.3 MJ ME/kg and 19.6 % crude proteins, and from 25 kg average live weight until the end of test the diet consisted of 13.6 MJ ME/kg and 17.4 % crude proteins.

Modeling growth

For the modeling of live weight growth and the growth of the main tissues (muscle, fat and bones), the asymmetric S-function with one flexible inflection point was used. This function is in fact generalised form of logistic function expressed as follows:

$$f(t)= \frac{A}{(1+be^{-c\gamma t})^{1/\gamma}} \qquad (1)$$

Parameters *A* denotes maximum growth capacity in the period of interest, or biological maximum growth; and *g* is a coefficient of asymmetry which regulates the influence of live weight at certain time *f(t)* and current biological potential at that time *(A-f(t))*. Model function (1) is also known as generalised logistic function. For this growth function, parameter estimation on the basis of the given measurement data is a very demanding numerical procedure, which cannot always be successfully carried out by ready-made software such as Mathematica (Wolfram Research, Champaign, Il, USA), Mathlab (MathWorks, Natick, MA, USA), SAS (SAS Institute Inc., Cary, NC, USA) and Statistica (StatSoft, Inc. Tulsa, OK, USA). In this paper, estimation of the parameter vector $a=(A, b, c, \gamma) \in R^4$ for some model growth function $t \rightarrow f(t, a)$ is estimated on the basis of measurement data (t_i, y_i), i=1, ..., m, where $0<t_1<\ldots<t_m$, and $y_i>0$, primarily by applying the least absolute deviations principle (Cadzow 2002, Bazaraa *et al.* 2006). Sometimes, it is possible that among the data severe measurement errors or poor measurement samples known in the literature as »outliers« or »wild points« appear (Watson 1980). Such data might lead not only to unreliable, but very often to wrong conclusions. Assuming that the model-function very well describes the behavior of most data, the least absolute deviations principle can be successfully applied for the purpose of detecting outliers. On the other hand, by using known properties of least absolute deviations approximation it is possible to simplify the minimising function significantly, by which parameters of the growth function are estimated. If the measurement data are contaminated only by normal distributed random errors, least absolute deviations approximation may be used as an excellent initial approximation for searching for the best least squares approximation.

The assessment of the parameters of generalised logistic function using least absolute deviations method.

If among the measurement data (t_i, y_i), i=1,…, m, some wild points appear, it is reasonable to assess the optimal parameters $(A^*, b^*, c^*, \gamma^*) \in R^4$ of the model-function (1) by minimization of the sum of absolute deviations, using LAD (Least Absolute Deviations) method, i.e.

$$\min_{(A, b, c, \gamma) \in R^4} F(A, b, c, \gamma)=F(A^*, B^*, c^*, \gamma^*) \qquad (2)$$

$$\text{where } F(A, b, c, \gamma) = \sum_{i=1}^{m} \left| \frac{A}{(1+be^{-c\gamma t_i})^{1/\gamma}} - y_i \right|$$

From the numerical view, minimisation of the non-differentiable functional F with 4 variables is extremely complex and unstable problem which can be reduced to solution of m problems of minimisation of the 3-variable function (Sabo & Scitovski 2008). If the assumption is that problem (2) has a solution A^*, b^*, c^*, γ^*, than:

$$F(A^*, b^*, c^*, \gamma^*) \geq \sum_{i=1}^{m} \left| \frac{A(b^*, c^*, \gamma^*)}{(1+b^* e^{-c^*\gamma t_i})^{1/\gamma^*}} - y_i \right| \quad (3)$$

where $A(b^*, c^*, \gamma^*)$ is weighted median of the numbers $y_i(1+b^* e^{-c^*\gamma^* t_i})^{1/\gamma^*}$, i=1,…, m with weights

$$\omega_i = \frac{1}{(1+b^* e^{-c^*\gamma^* t_i})^{1/\gamma^*}} \quad i=1, ..., m \quad (4)$$

In that sense the equality in (3) holds if $A^*=A(b^*, c^*, \gamma^*)$. According to the properties of the weighted median there exist $\mu \in \{1, ..., m\}$ so that $A(b^*, c^*, \gamma^*)=y_\mu(1+b^* e^{-c^*\gamma^* t_\mu})^{1/\gamma^*}$. If we denote

$$F_\mu(b, c, \gamma) = \sum_{i=1}^{m} \left| \frac{y_\mu(1+be^{-c\gamma t_\mu})^{1/\gamma^*}}{(1+be^{-c\gamma t_i})^{1/\gamma^*}} - y_i \right| \quad (5)$$

It is obvious that

$$\min_{(A, b, c, \gamma) \in R^4} F(A, b, c, \gamma) = \min_{\mu=1, ..., m} \min_{b,c,\gamma,>0} F_\mu(b, c, \gamma) \quad (6)$$

For each $\mu \in \{1, ..., m\}$ it is needed to solve the problem of three-dimensional minimisation of the functional F_μ:

$$\min_{(b, c, \gamma) \in R^3} F_\mu(b, c, \gamma) = F_\mu(b_\mu, c_\mu, \gamma_\mu) \quad (7)$$

For this purpose *NMinimize* instruction of the program package Mathematica 6.0 (Wolfram Research, Champaign, Il, USA) is used. If $\mu^* \in \{1, ..., m\}$ is such that

$$\min_{\mu=1, ..., m} F_\mu(b_\mu, c_\mu, \gamma_\mu) = F_{\mu^*}(b_{\mu^*}, c_{\mu^*}, \gamma_{\mu^*}) \quad (8)$$

Than optimal parameters for the solution of the problem (2) are:

$$b^* = b_{\mu^*},\ c^* = c_{\mu^*},\ \gamma^* = \gamma_{\mu^*},\ A^* = y_{\mu^*}(1-b^* e^{-c^*\gamma^* t_{\mu^*}})^{1/\gamma^*} \quad (9)$$

The point of inflection denotes the moment at which progressive growth ceases and growth retardation starts; it is calculated as follows:

$$I = \left(\frac{1}{c\gamma} 1n \frac{b}{\gamma};\ \frac{A}{(1+\gamma)^{1/\gamma}}\right) \quad (10)$$

The stages of growth are determined by the points t_B and t_C which are calculated according to the following formulae:

$$t_B = \frac{1}{c\gamma} 1n \frac{2b}{\gamma(\gamma+3)+\gamma\sqrt{(\gamma+1)(\gamma+5)}} \ \ and\ \ t_C = \frac{1}{c\gamma} 1n \frac{2b}{\gamma(\gamma+3)-\gamma\sqrt{(\gamma+1)(\gamma+5)}} \quad (11)$$

Point B denotes a maximum in the region of progressive growth (convex region) and point C is a minimum value in the region of degressive growth (concave region). Interval ($t<t_B$) is called the stage of preparing growth; ($t_B<t<t_C$) represents the stage of intensive growth and ($t>t_C$) is the stage of growth retardation. The asymmetric S-function was analysed using Mathematica 6.0 program package (Wolfram Research, Champaign, Il, USA) and SAS/STAT 9.1 (SAS Institute Inc., Cary, NC, USA) which were also used to prepare some of the figures.

Results and discussion

Asymmetric S-function in assessment of maximum live weight growth of pigs

The parameters of asymmetric S-function used in the depiction of live weight growth of investigated pigs are presented in Table 1. Figure 1 shows the resulting growth curve of barrows and gilts included in the study; the curve was fitted to the data using least absolute deviations method. It can be noted that assessed maximum live weight growth was 233.25 kg for barrows and 179.79 kg for gilts. Solanes *et al.* (2005) reported similar pattern of growth in Batalle hybrids, although lower live weight was achieved (average live weight of 102.4 kg in 179.6 days). In this study to achieve similar average live weight (103 kg) was required less days (163.2 days for barrows and 161.4 days for gilts). Reixach *et al.* (2008) reported similar results regarding the change of live weight in barrows. At the age of 200 days Duroc pigs had 124.42 kg and double line Duroc pigs had 121.49 kg. Schinckel *et al.* (2009) used different nonlinear functions (Bridges, Gompertz and Michaelis-Mentens) for the growth analysis of different pig hybrids. Authors found that Michaelis-Mentens function estimated higher final weight of pigs (379.3 kg) when compared to Bridges (238.7 kg) and Gompertz (211.9 kg) function on the same data. Kastelic *et al.* (1993) estimated final weights (biological maximum) in the interval between 208.51 kg and 233.67 kg, depending on the model used. The results on growth capacity similar to those shown in the present study were found by Reiland (1978) who predicted maximal live weight of landrace type boars to 235 kg. Koivula *et al.* (2008) reported that maximal live weights of Finnish Large White (gilts, barrows and boars) were 201.3 kg on average. The literature values of the final live weights indicate large differences between the breeds (Wellock *et al.* 2003; Strathe *et al.* 2010). Beside genetic and environmental influences, estimated weights of pigs can vary because of some models do not estimate final weights correctly.

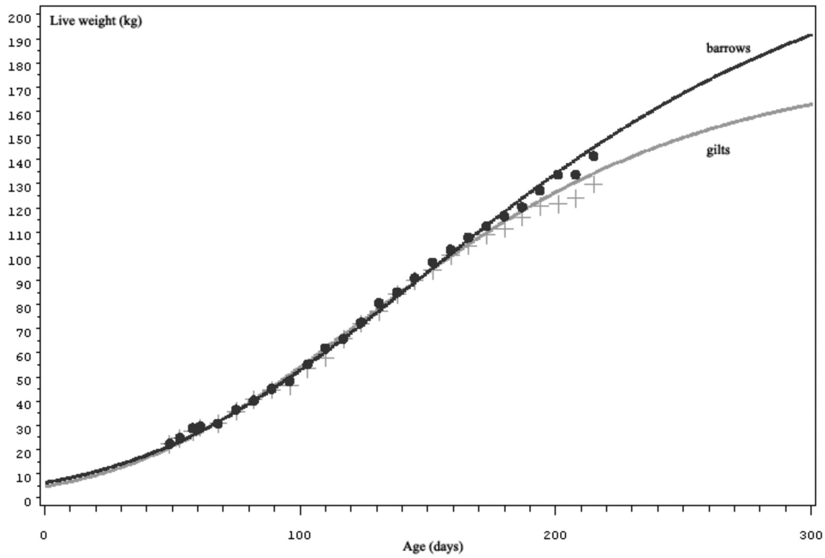

Figure 1
Live weight growth curves of barrows and gilts

Table 1
Parameters of the asymmetric S-function and the points that determine growth stages of investigated pigs

Parameter	Barrows	Gilts
A^*, kg	233.25	179.79
γ^*	0.1575	0.1463
b^*	0.7637	0.6975
c^*	0.0675	0.0882
I, days; kg	(148.50; 92.16)	(121.04; 70.70)
$T_{B,}$ days; kg	(51.64; 22.93)	(41.59; 17.35)
$T_{C,}$ days; kg	(245.36; 164.80)	(200.48; 126.74)

Asymmetric S-function in depiction of muscle tissue growth

Table 2 shows the parameters of asymmetric S-function used in the depiction of muscle tissue growth of investigated pigs and the points that denote growth stages at the resulting S-curve which is presented in the Figure 2. From the Figure 2 it can be observed that the growth of barrows and gilts included in this study was described by the model, and that the curve fitted well to the data. The biological maximum of the muscle tissue growth was estimated to 75.79 kg and 75.74 kg for barrows and gilts, respectively. Using the model for the growth of live weight, it can be calculated that the point of muscle growth saturation for gilts and barrows is reached at the 102 kg (161.8 days) and 135 kg (201.2 days) of the live weight, respectively. Since after this point the rate muscle growth is decreasing and weight gain of the pigs is obtained mostly from growth of fat, these points can be regarded as the optimal live weights for slaughter in terms of maximal utilisation of muscle tissue growth. Vincek *et al.* (2008), using the same principles i.e. combining the information obtained by modeling of live

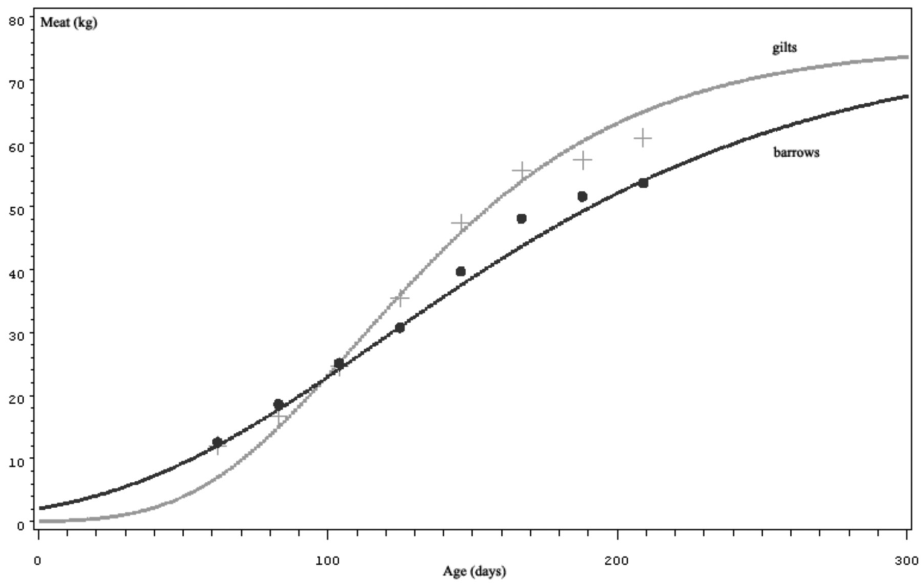

Figure 2
Growth curve of muscle tissue of gilts and barrows

weight and muscle tissue growth, calculated the optimal slaughter weight to be 130 kg for intensively fed pigs and 114 kg for the pigs fed restrictively. Schinckel *et al.* (2002), predicted muscle mass of 27.2 kg, 31.2 kg and 35.4 kg at the age of 146, 160 and 174 days, respectively. Autors concluded that the rate of muscle mass forming declines at the end of the fattening period, but the time and the rate of the reduced growth depend on the genetic structure of animals.

Table 2
Parameters of growth curve and points which determine stages of muscle tissue growth

Parameter	Barrows	Gilts
A^*, kg	75.74	75.79
γ^*	0.0676	0.0426
b	0.2753	0.3443
c	0.1756	0.4449
I, days; kg	(118.28; 28.78)	(110.12; 28.46)
T_B, days; kg	(34.73; 6.36)	(53.39; 6.06)
T_C, days; kg	(201.85; 52.51)	(161.85; 52.25)

Asymmetric S-function in depiction fat tissue growth

In Table 3 the parameters of asymmetric S-function and the points which determine the stages of fat tissue growth in the carcasses of studied pigs are shown. The growth of fat tissue of gilts was described using the function with the biological maximum set at 31.1 kg, while the one of barrows was estimated to 62.63 kg. Figure 3 presents the growth of fat tissue of gilts and barrows described using the model with estimated parameters. From the presented results it can be seen that the growth of fat tissue accelerates in the later stages. Similar findings on fat tissue growth were presented by Kouba *et al.* (1999) in the study of development of various fat depots during the growth of pigs of different carcass composition. When compared to other fat depots, the authors conclude that intramuscular fat develops more in genetically meaty than genetically fatty pigs. According to their opinion, it might be because of selecting reduced subcutaneous fat only.

Later completion of fat tissue growth was determined by many authors (Davies & Kallweit 1979, Gu *et al.* 1992), and their results were confirmed in this study as well. Most studies dealing with growth of pigs lead to the conclusion that body weight and back fat thickness significantly differ between breeds and sexes.

Table 3
Growth curve parameters and the points which determine the stages of fat tissue growth

Parameter	Barrows	Gilts
A^*, kg	62.64	31.10
γ^*	0.0457	0.0475
b^*	0.25916	0.2322
c^*	0.1799	0.2331
I, days; kg	(210.98; 23.56)	(143.00; 11.71)
T_B, days; kg	(91.51; 5.04)	(54.35; 2.51)
T_C, days; kg	(330.45; 43.21)	(231.66; 21.46)

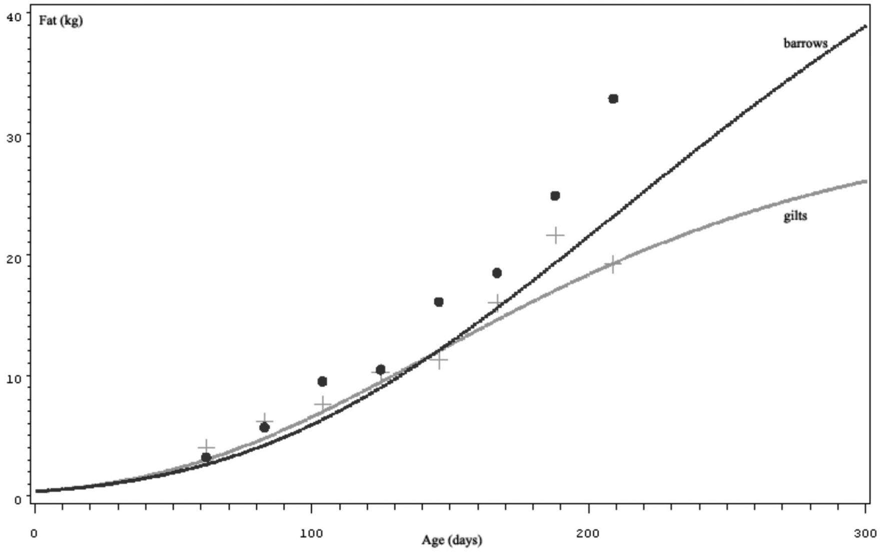

Figure 3
The curve of fat tissue growth of barrows and gilts

Asymmetric S-function in depiction bone growth

In this study bone growth increases proportionally with the body, and estimated parameters of the curve are shown in Table 4 and Figure 4. Bone growth of gilts is described using the function with the biological maximum set at 10.94 kg, while the one of barrows was estimated at 32.75 kg. The stage of intensive bone growth of the studied barrows lasted approximately 419 days. Furugouri *et al.* (1981) reported that the increase of body weight is proportional to the increase of length and diameter of bones in pigs between 30 and 150 kg, which shows that the shape of bones is formed in the earliest stage of growth. Exploring the influence of a breed on the proportion of bones in pig carcasses, Žgur *et al.* (1995) reported that larger percentage of bones was found in Duroc crossbreeds when compared to other genotypes. Bone development is faster in younger animals, but starts to decline when an animal reaches a market weight. Although the rate of bone growth slowly declines as the animal enters later stages of life, the skeleton is still growing, only considerably more slowly.

Table 4
Parameters of growth curve and the points which determine stages of bone growth

Parameter	Barrows	Gilts
A^*, kg	32.75	10.94
γ^*	0.0507	0.2107
b^*	0.1737	0.9137
c^*	0.0927	0.0706
I, days; kg	(262.09; 12.35)	(98.64; 4.42)
T_B, days; kg	(52.62; 2.66)	(27.96; 1.17)
T_C, days; kg	(471.56; 22.62)	(169.31; 7.81)

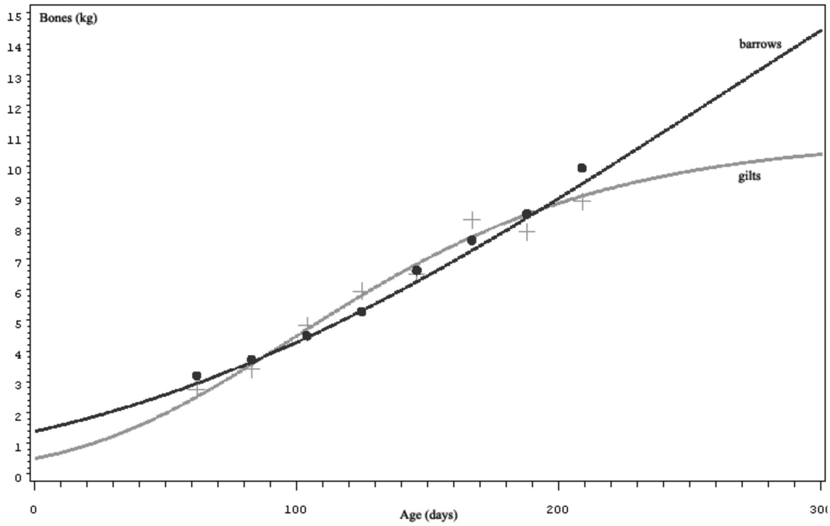

Figure 4
Growth curve of bones of barrows and gilts

In present study, the biological maximum of growth and coefficient of asymmetry, in contrast to previous studies, was calculated on the basis of recorded data on the growth of live weight. Data obtained by dissection of sacrificed animals were used to calculate the biological maximum (A) of the tissues and their coefficient of asymmetry. Asymmetric S-curve appears to be a good mathematical model for the prediction of live weight and muscle tissue growth, while fat tissue and bone growth were not described so well. Consequently, there is a need of constant review of the tools in the assessment of growth of certain tissues in commercial pig production. Estimation of the maximum growth of live weight and the weight of economically important tissues of pigs based on the collected data proved to be possible, despite the large number of parameters included in the model. The prediction of optimum slaughter age/weight, on the basis of such model represent a contribution of this paper to the practice.

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