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BONE STRENGTH (*ossis tibiae*) OF NATIVE PIGS ZŁOTNICKA SPOTTED BREED AND CROSSBREDS OF POLISH LARGE WHITE AND PoLISH LANDRACE PIGS

WYTRZYMAŁOŚĆ KOŚCI PISZCZELOWYCH (*ossis tibiae*) ŚWIŃ RODZIMEJ RASY ZŁOTNICKIEJ PSTREJ ORAZ MIESZAŃCÓW RAS WIELKIEJ BIAŁEJ POLSKIEJ I POLSKIEJ BIAŁEJ ZWISŁOUCHEJ

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ABSTRACT

The purpose of this study was to compare the bone strength traits in two groups of pigs different in terms of genetic value, fast growth capability and meat deposition in the body. The study covered 33 fatteners of the Złotnicka Spotted breed (ZŁP) and 20 crossbreds F_1 (Polish Large White x Polish Landrace). Tibial bones were obtained following slaughter and evaluated in terms of properties and geometry, as well as bending and compressive strength. Mineral composition of the bone tissue was also established, i.e.: ash, Ca, P, Na, K, Zn and Mg. The significance of differences between the traits demonstrated by pigs in both groups subject to the study was estimated, with calculated overall correlations between the primary bone properties. The results confirmed significant differences in terms of geometry of the bones in both animal groups. In the ZŁP breed pigs, compared to the F_1 crossbred group (PLW x PL), the outside and inside diameters of the tibial shaft were smaller ($P \leq 0.01$), yet the average thickness of the wall of the bone was slightly larger. The bending force required to fracture the bone turned out to be lower in Złotnicka Spotted pigs, the opposite of the results obtained with regard to the compressive strength. Furthermore, calcium content, calcium-phosphorus ratio (Ca : P) and sodium content were highly statistically or significantly larger in the bone tissue of the Złotnicka Spotted pigs. Consequently, the final results show that the bone strength demonstrated by modern pig breeds subject to intensive selection focused on high growth rate and increased meat deposition is in no way lower than the same trait recognized in the Złotnicka Spotted breed kept in preservative breeding conditions.

KEYWORDS: pigs, bone, bone strength, minerals

STRESZCZENIE

Celem badań było porównanie cech wytrzymałości kości świń dwóch grup różniących się wartością genetyczną pod względem zdolności szybkiego tempa wzrostu i odkładania mięsa w ciele. Badaniom poddano 33 tuczniki rasy złotnickiej pstrej (ZŁP) i 20 mieszańców F_1(wielka biała polska x polska biała zwisłoucha), pobrano po uboju kości piszczelowe i oceniano właściwości ich budowy geometrycznej, a także wytrzymałość na obciążenia zginające i ściskające. Oznaczono też skład mineralny tkanki kostnej tj.: popiół, Ca, P, Na, K, Zn i Mg. Obliczono istotność różnic między badanymi cechami obu grup świń i wyliczono korelacje ogólne między ważniejszymi właściwościami kości. Uzyskane wyniki potwierdziły istotne różnice w budowie geometrycznej kości świń obu badanych grup zwierząt. U świń rasy ZŁP w porównaniu do F_1(wbp x pbz), średnice zewnętrzne i wewnętrzne trzonu kości były mniejsze ($P \leq 0.01$) lecz średnia grubość ściany kości była nieco większa. Siła zginająca potrzebna do złamania kości okazała się także mniejsza u świń rasy złotnickiej pstrej, odwrotnie niż w przypadku wytrzymałości na ściskanie. Ponadto, zawartość wapnia i proporcje Ca:P oraz zawartość sodu były w sposób statystycznie wysokoistotny lub istotny większe w tkance kostnej świń rasy złotnickiej pstrej. Uzyskane wyniki nie wskazują więc na to aby wytrzymałość kości u nowoczesnych świń, poddawanych intensywnej selekcji na tempo wzrostu i zwiększone odkładanie mięsa, była mniejsza w stosunku do pozostającej w hodowli zachowawczej rasy złotnickiej pstrej.

SŁOWA KLUCZOWE: świnie, kości, wytrzymałość kości, skład mineralny

STRESZCZENIE SZCZEGÓŁOWE

Prawidłowy rozwój i ukształtowanie odpowiednich właściwości szkieletu kostnego u zwierząt gospodarskich decyduje w dużej mierze o ich produkcyjności, szczególnie przy ich długotrwałym użytkowaniu i osiąganiu przez nie dużej masy ciała. U świń pewne zaburzenia w kształtowaniu prawidłowego kośćca mogą wynikać z selekcji na duże tempo wzrostu i zwiększenie umięśnienia, co może zmieniać właściwe proporcje między rozwojem mięśni i kośćca [21]. Celem pracy było porównanie właściwości mechanicznych kości dwóch grup świń różniących się produkcyjnością (tempo wzrostu, stopień umięśnienia) tj. świń rasy złotnickiej pstrej (ZŁP) pozostających w warunkach hodowli zachowawczej i mieszańców dwóch ras poddawanych silnej selekcji w kierunku tempa wzrostu i zwiększonej mięsności (wielkiej białej polskiej - wbp i polskiej białej zwisłouchej – pbz)

Oceniano parametry wytrzymałości kości u 33 tuczników rasy złp ubijanych przy masie ciała około 110 kg i 20 mieszańców (wbp x pbz) przy masie ciała około 120 kg. Wiek tuczników był zbliżony i wynosił około 200 dni. Badano wytrzymałość kości piszczelowych na zginanie i ściskanie przy wykorzystaniu aparatu INSTRON 8874 sprzężonego z komputerem rejestrującym podstawowe parametry przy obciążeniu zginającym i ściskającym (rys. 1 i 2). Pomiary budowy geometrycznej grubości kości

przeprowadzono w sposób podany na rys. 3. Ponadto, oznaczono zawartość popiołu, Ca, P, Ca:P, Na, K, Zn i Mg w suchej masie tkanki kostnej.

Wykazano szereg istotnych różnic między porównywanymi grupami świń w badanych parametrach wytrzymałości i budowie geometrycznej kości. Kości piszczelowe świń ZŁP miały mniejsze średnice zewnętrzne i wewnętrzne kości ($P \leq 0.01$) i nieco większą średnią grubość ściany trzonu kości. Siła zginająca potrzebna do złamania kości była istotnie mniejsza u świń rasy ZŁP, a naprężenie ściskające większe niż u mieszańców F_1 ($P \leq 0.01$). Istotne różnice między porównywanymi grupami świń wystąpiły też w zawartości wapnia ($P \leq 0.01$), proporcji Ca:P ($P \leq 0.01$) i zawartości sodu ($P \leq 0.05$). Tkanka kostna świń ZŁP wykazała wyższy stopień mineralizacji niż mieszańców wbp x pbz. W badaniach wykazano, że kości świń rasy ZŁP cechowały się mniejszą wytrzymałością na obciążenia zginające i większą wytrzymałością na obciążenia ściskające niż kości świń mieszańców PLW x PL.

INTRODUCTION

Correct growth and development of appropriate properties of endoskeleton in farm animals exerts substantial influence on their productivity, particularly in case of long-term utilization and large body weights gained by these animals. Both osteochondrosis and dyschondroplasia syndromes, involving growth related disorders and ossification in young, fast growing animals are well known [18; 21; 22]. In case of pigs, these disorders may result from the selection practices aimed at high body weight growth rate and increase in meatiness, both affecting the appropriate balance between the muscular and skeletal development [21].

Providing adequate animal nutrition using fodders containing appropriate calcium and phosphorus amounts and ratios is of outmost importance with regard to correct mineralization processes of the bone tissue [3; 4; 5]. Environmentally friendly farm production is also fraught with certain limitations in terms of the amount of mineral components present in the soil and fodders, which may increase with time [9]. According to Fandrejewski [6], the demand for major nutrients in pigs has not been entirely explored, particularly with regard to animals of diversified growth potential, which suggest that apart from the calcium and phosphorous demand the resistance of bones to mechanical loads should be the additional analysed criterion.

The purpose of this study was to compare mechanical properties of bones taken from two dissimilar breeds of pig that differed in terms of selection and improvement degree, i.e. Złotnicka Spotted and F_1 crossbreds of Polish Large White and Polish Landrace (PLW x PL). The Złotnicka Spotted breed constitutes a native breed kept as part of the preservative breeding program.

MATERIAL AND METHODS

The study covered 53 fatteners obtained from an ecological breeding farm. This group comprised of 33 Złotnicka Spotted pigs (ZŁP) and 20 F_1 crossbreds (PLW x PL). The animals were kept in identical conditions – in groups, on deep straw and fed in accordance with the Polish Pig Feeding Standards [13]. The ZŁP group pigs were slaughtered with an approximate body weight of 110 kg, while the crossbreds were slaughtered weighing approximately 120 kg. The age of the pigs in both groups was similar and amounted to approximately 200 days. After a 24h carcass cooling period and subsequent division of carcasses into major cuts, the femur and tibial bones were dissected from the ham. These were then kept frozen at –25°C until the analysis. The strength tests were carried out on the tibial shaft (*corpus ossis tibiae*) and the basic mineral composition was determined on the femur shaft (*corpus ossis femoris*).

The strength tests were carried out at the Biomedical Engineering Department. The three point bending test carried out on the whole tibial bone was followed by compression tests performed on a cross section of the bone. The bone crushed as a result of bending was cut in 10 mm thick segments, perpendicularly to the bone's axis, using band saw equipment. Compressive strength was measured on segment immediately adjacent to the fracture resulting from the bone bending test.

Mechanical properties of the bones were determined by measuring the bending and compressive strength with the use of INSTRON 8874 tensile testing machine connected to a computer recording basic strength parameters. Based on these data bone failure diagrams were prepared. Figure 1 shows two demonstration diagrams which represent the bending process for the middle cross section of the bone (diagram a) and compression process for the cut out segment (diagram b).

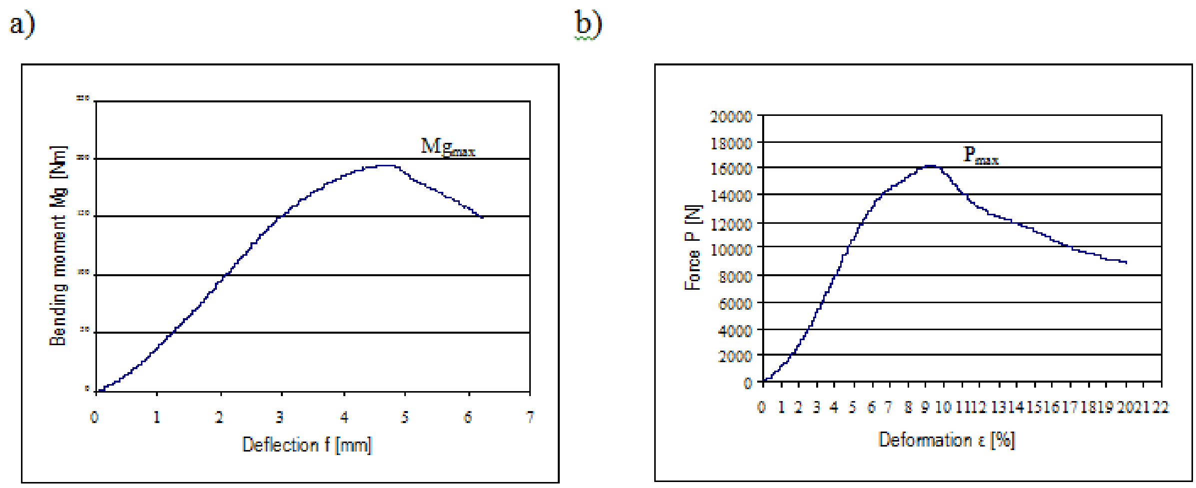

Fig. 1. Demonstration diagram of bone bending (a) and bone compression (b)
Rys. 1. Przykładowy wykres zginania kości (a) i ściskania kości (b)

The bending load tests were carried out in accordance with the three point bending test procedure with distance between the supports a = 120 mm. The analysed bones were placed on the supports in exactly the same position, with tibial tuberosity (*tuberositas tibiae*) pointing up.

The loading force P was applied in the middle of the distance between the supports, in accordance with the diagram presented in Fig. 2, with actuator rate of travel v = 1 mm/min. The fundamental values were recorded: force, actuator travel, test time.

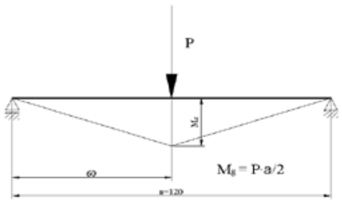

Fig. 2. Diagram representing sample loading through bending and the means of determining the bending moment for the middle cross section of the sample.
Rys. 2. Schemat obciążenia próbki zginanej i sposób określenia momentu gnącego dla jej środkowego przekroju

The bending test results obtained from each test enabled establishing the bending moment value M_{gmax} Nm (Fig. 1a), section bending modulus W_x mm^2 using AutoCad and calculating the bending stress in accordance with the following formula:

$\sigma_g = M_{gmax}/W_{x,}$ MPa

The compressive strength tests of the bone were carried out on 10 mm thick bone segments compressed until a deformation ε of 20% of the initial dimension, i.e. h = 2.0 mm, was reached. Data obtained from the tensile testing machine was used for reading the compressive force value P_{max} kN (Fig. 1b) and calculating the sectional area F mm^2 which made it possible to determine the applicable compressive stress:

$\sigma_c = P_{max}/F$, MPa

Measurements of bone thickness were carried out on a segment of the bone that was immediately adjacent to the compressive load test point from the side of the knee joint, in accordance with the relevant diagram (fig. 3.). Electronic callipers were used to measure the outside (APz) and inside (APw) diameter of the bone on the AP (anterior – posterior) plane as well as the outside and inside diameters of the bone on the lateral (B) plane.

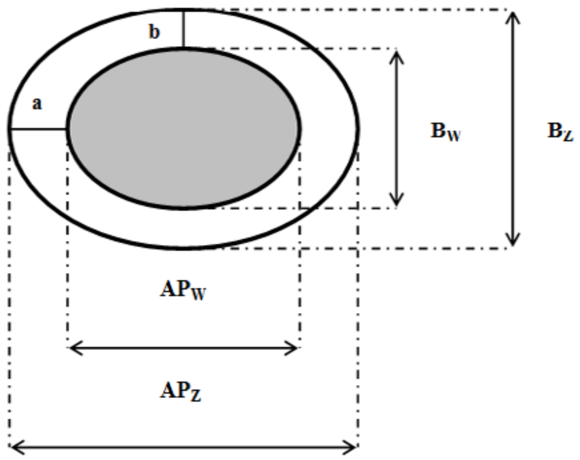

Fig. 3. Diagram representing the measurement of outside and inside diameters of the bone on AP and B-lateral planes.
Rys. 3. Schemat pomiaru średnic zewnętrznych i wewnętrznych kości w płaszczyźnie AP i bocznej B

The relative bone thickness was calculated following a similar method to the one provided by Radzki *et al.* [15]:

Thickness of the tibial bone on AP plane; $a = AP_Z – AP_W/2$, mm

Grubość kości piszczelowej w płaszczyźnie AP; $a = AP_Z – AP_W/2$ [mm]

Thickness of the tibial bone on B plane; $b = B_Z – B_W/2$, mm

Grubość kości piszczelowej w płaszczyźnie B; $b = B_Z – B_W/2$ [mm]

Determination of ash content and the basic mineral composition of the bone were carried out on samples which were pre-ground, dried through lyophilization and then re-ground in a ball grinder. The ash content was determined by combusting the sample in a muffle furnace at 600°C. Bone mineralization was evaluated in wet condition; in an ETHOS PLUS microwave mineralizer, using nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). The analysis focused on the content of sodium (Na), potassium (K), zinc (Zn), magnesium (Mg) and calcium (Ca), utilizing atomic absorption spectrometry on SOOLAR 969 equipment from UNICAM. The analytical procedure complied with the applicable standards. Phosphorous determination was effected by comparison with standard solution, using spectrophotometry with a wavelength of 430 mm set on LAMBDA 25 apparatus from PARKIN-ELMER and again, maintaining full compliance with all applicable standards.

The obtained test and determination results were analyzed statistically. Average values (x) and standard deviation (s) were calculated for all analyzed traits. The significance of differences between the groups of pigs subject to comparison was assessed using the t-test. Overall correlations were established. The calculations were made using STATISTICA 8 PL [17] computer software.

RESULTS AND DISCUSSION

As opposed to high yield PLW and PL pigs, the Złotnicka Spotted breed is distinguished by a relatively primitive conformation, poor musculature of the back and hams, as well as slower growth rate [16]. Simplified carcass characteristics of both groups of pigs (Table 1) revealed highly significant differences in fatness and musculature of pig carcasses of the breeds subject to the study. The Złotnicka Spotted animals demonstrated slower growth rate, smaller body weight, poorer musculature and larger back fat thickness (P ≤ 0.01).

Table 1. Carcass characteristics
Tabela 1. Charakterystyka rzeźna tuczników

Trait -Cecha	Breed - Rasa: Złotnicka Spotted Złotnicka pstra x	s	Crossbred (PLWxPL) F_1 (wbp x pbz) x	s
Number, n Liczebność, n	33		20	
Body weight at slaugther, kg Masa ciała przy uboju, kg	107.12^{A}	7.23	119.80^{B}	13.98
Cold carcass weight, kg Masa tuszy zimnej, kg	77.23^{A}	7.56	89.93^{B}	12.83
Av. backfat thickness from 5 meas, mm Śr. grubość słoniny z 5 pom., mm	27.61^{A}	6.81	20.05^{B}	12.83
Loin cross section area, cm^2 Powierzchnia przekroju polędwicy, cm^2	32.54^{A}	4.55	52.12^{B}	11.80

Means in the same row with different letters are significantly different: A,B - (P ≤ 0.01)
Wartości w wierszach oznaczone różnymi literami różnią się istotnie: A,B przy P ≤ 0.01

The measurements of the bone cross section revealed considerable differences between the compared groups of pigs in terms of spatial construction of the limb bones. High meat yield crossbred PLW and PL fatteners demonstrated considerably larger bone cross sections than the Złotnicka Spotted specimens. The bone cross section shape dimensions (Table 2), against expectations, revealed smaller outside and inside diameters on the AP plane as well as on the lateral plane in Złotnicka Spotted pigs than in case of the crossbreds (P ≤ 0.01). The relative bone wall thickness on both planes AP and B was slightly larger in the Złotnicka Spotted breed (4.24 compared to 3.94 mm and 3.24 compared to 2.96 mm), however, the differences between the analysed breeds of pig were not statistically significant. A considerable influence on the shape and cross section of the bone may be exerted by the way the animals are kept, either increasing or limiting their freedom of movement [7].

Table 2. Bone cross section shape, mm
Tabela 2. Wymiary przekroju kości piszczelowej, mm

Trait -Cecha	Breed - Rasa: Złotnicka Spotted Złotnicka pstra		Breed - Rasa: Crossbred (PLWxPL) F_1 (wbp x pbz)	
	x	s	x	s
Outside diameter AP_Z Średnica zewnętrzna AP_Z	24.53^A	2.01	28.61^B	2.58
Inside diameter AP_W Średnica wewnętrzna AP_W	16.05^A	1.98	20.73^B	3.14
Av. wall thickness a Względna grubość a	4.24	0.98	3.94	0.64
Outside diameter B_Z Średnica zewnętrzna B_Z	16.13^A	1.43	18.68^B	1.27
Inside diameter B_W Średnica wewnętrzna B_W	9.67^A	1.37	12.75^B	1.90
Av. wall thickness b Względna grubość b	3.24	0.71	2.96	0.38

Means in the same row with different letters are significantly different: A,B - ($P \le 0.01$)
Wartości w wierszach oznaczone różnymi literami różnią się istotnie: A,B przy $P \le 0.01$

The mechanical strength of the bone depends on a number of factors, including but not limited to spatial construction and geometry of the bone that are of considerable importance [1; 3; 11; 19]. The identified differences in geometry of the bone were reflected during the measurements taken under bending and compressive loads (Table 3).

Bending forces occurring during bone fracture depend largely on the geometrical shape and dimensions of the bone, whereas the measurement of the compressive force allows comparing bones of various shapes and sizes [4]. Our study revealed significant differences between the two groups of animals subject to comparison in nearly all bone strength indexes.

The bending force required to rupture the bone was smaller in the Złotnicka Spotted animals than it was in case of the F_1 crossbreds (2.99 compared to 3.41 kN; $P \le 0.01$), similar results were obtained with regard to the bending moment M_{gmax} (179.65

Table 3. Bone strength at bending load and compressive load
Tabela 3. Wytrzymałość kości przy obciążeniu zginającym i ściskającym

Trait -Cecha	Breed - Rasa			
	Złotnicka Spotted Złotnicka pstra		Crossbred (PLWxPL) F_1 (wbp x pbz)	
	x	s	x	s
Bending force P, kN Siła zginająca P, kN	2.99^{A}	0.71	3.41^{B}	0.58
Bending moment M_{gmax}, Nm Moment gnący, M_{gmax}, Nm	179.65^{a}	42.51	204.46^{b}	34.98
Section modulus W_x, mm^2 Wskaźnik przekroju W_x, mm^2	598.14^{A}	112.05	930.83^{B}	124.54
Bending stress σ_g, MPa Naprężenie zginające σ_g, MPa	306.25^{A}	75.93	220.83^{B}	32.83
Stress force P_{max}, kN Siła ściskająca P_{max}, kN	19.47	3.50	18.29	4.10
Cross sectional area F, mm^2 Pole przekroju F, mm^2	213.17^{A}	27.02	259.42^{B}	33.22
Compressive stress σ_c, MPa Naprężenie ściskające σ_c, MPa	92,10^{A}	16,91	70,98^{B}	15,39

Means in the same row with different letters are significantly different: a,b - P ≤ 0.05; A,B - P ≤ 0.01
Wartości w wierszach oznaczone różnymi literami różnią się istotnie: a,b przy P ≤ 0.05 i A,B przy P ≤ 0.01

compared to 204.46 Nm; P ≤ 0.05). The sectional bending modulus W_x was also lower (598.14 compared to 930.83 mm^2; P ≤ 0.01). Bending stress σ_g was significantly higher (306.25 compared to 220,83 MPa; P ≤ 0.01). Compressive force P_{max} was similar for the bones of both groups (19.47 compared to 18.29 kN). The cross sectional bone area F calculated on the basis of the compression formula was smaller in the Złotnicka Spotted specimens than it was in case of the crossbreds (213.17 compared to 259.42 mm^2; P ≤ 0.01). However, compressive stress σ_c was significantly higher in the Złotnicka Spotted group than it was in the crossbreds (92.10 compared to 70.98 MPa; P ≤ 0.01). This result might have been affected by a larger bone shaft wall thickness in these animals.

Considerable difficulty in terms of correct interpretation of the aforesaid test results may be attributed to a complete lack of literature providing data required for a comprehensive comparison of all obtained results with information gathered by other authors. Numerous studies focusing on bone strength observable in pigs utilize other research techniques, frequently non-invasive, and different types of bones [4; 8; 10; 12; 20]. The research conducted by Pawłowska [11] on piglets proved, among other issues, that, similarly to our study, the animals demonstrating increased bending strength were also the ones with larger cross sectional area of the bone.

Table 4. Mineral content g/kg
Tabela 4. Skład mineralny kości g/kg

Trait -Cecha	Breed - Rasa: Złotnicka Spotted Złotnicka pstra x	s	Crossbred (PLWxPL) F_1 (wbp x pbz) x	s
Dry matter, 5 Sucha masa, %	85.01	2.01	83.85	2.34
Ash, % Popiół, %	60.35	2.54	60.32	2.27
Phosphorous, P Fosfor, P	117.08	8.67	118.37	11,01
Calcium, Ca Wapń, Ca	281.23^{A}	19.63	253.71^{B}	23.96
Ca : P	2.42^{A}	0.26	2.16^{B}	0.25
Sodium, Na Sód, Na	7.27^{a}	0.50	7.57^{b}	0.58
Potassium, K Potas, K	0.704	0.112	0.728	0.061
Zinc, Zn Cynk, Zn	0.115	0.015	0.115	0.016
Magnesium, Mg Magnez, Mg	4.43	0.56	4.50	0.37

Means in the same row with different letters are significantly different: a,b ($P \leq 0.05$)
Wartości w wierszach oznaczone różnymi literami różnią się istotnie: a,b przy $P \leq 0.05$

Table 5. Overall correlation coefficients between bone shape and bone strength at bending and stress characteristics, (n = 53)
Tabela 5. Współczynniki korelacji ogólnej między wymiarami a cechami charakteryzującymi wytrzymałość kości dla wszystkich świń, (n = 53)

Correlations - Korelacje	AP_Z	AP_W	a	B_Z	B_W	b
Bending force P, kN Siła zginająca P, kN	$.39^{xx}$	$.42^{xx}$	-.12	$.38^{xx}$	$.33^{x}$	.02
Bending moment M_{gmax}, Nm Moment gnący, M_{gmax}, Nm	$.39^{xx}$	$.42^{xx}$	-.12	$.38^{xx}$	$.33^{x}$	.02
Section modulus W_x, mm^2 Wskaźnik przekroju W_x, mm^2	$.79^{xx}$	$.74^{xx}$	-.06	$.78^{xx}$	$.72^{xx}$	-.03
Bending stress σ_g, MPa Naprężenie zginające σ_g, MPa	$-.45^{xx}$	$-.36^{xx}$	-.08	$-.49^{xx}$	$-.43^{xx}$	-.01
Stress force P_{max}, kN Siła ściskająca P_{max}, kN	.07	-.06	.22	-.04	-.23	$.30^{x}$
Cross sectional area F, mm^2 Pole przekroju F, mm^2	$.60^{xx}$	$.53^{xx}$	.01	$.47^{xx}$	$.47^{xx}$	-,07
Compressive stress σ_c, MPa Naprężenie ściskające σ_c, MPa	$-.35^{x}$	$-.40^{xx}$	.17	$-.36^{xx}$	$-.51^{xx}$	$.30^{x}$

x – $P \leq 0.05$
xx – $P \leq 0.01$

Mechanical properties of bone tissue are conditioned by distinctive structure and chemical composition of the bone matrix, with collagen as its primary organic component and smaller amounts of osteocalcin and other conjugated proteins. The osteocalcin generated in osteoclasts combines with hydroxyapatite crystals comprised of calcium phosphate and deposited in the bone matrix during the mineralization process [2; 11]. The degree of bone mineralization is not constant, as the bone tissue is continually rebuilding itself and, additionally, its mineral composition depends on the function and role the given bone is to perform in the endoskeleton.

Table 4 presents the results obtained through our study that pertain to the mineral composition of the bone tissue in both groups of pigs subject to comparison. The dry matter, ash and calcium content meets the data referred to in the literature [14] for pig femurs. Significant differences between the group of ZŁP pigs and the crossbreds (PLW x PL) occurred with regard to the Ca content ($P \leq 0.01$), Ca : P ratio ($P \leq 0.01$) and sodium content ($P \leq 0.05$). The bone tissue of the ZŁP pigs demonstrated higher mineralization degree than the bone tissue in the F_1 (PLW x PL) group.

Reciprocal relations between the analysed traits pertaining to the cross sectional dimensions of the bone, strength related traits of the bone and the mineral composition of the bone tissue may be characterized by a number of correlations identified between these indexes (Table 5 and Table 6).

A number of mechanical properties that characterize the resistance of the bone to both bending and compressive loads were highly significantly correlated with the shape and geometry of tibial bones. The larger the outside and inside bone diameters were, the higher the bending force and bending moment proved to be, both on the anterior – posterior plane as well as the lateral plane ($P \leq 0.01$). The thickness of the wall for bones a and b was not significantly correlated with the bone’s bending strength. The bone stress under bending was smaller in case of bones with larger diameters ($P \leq 0.01$).

The bone diameters were not significantly correlated with the compressive force required to deform them, whereas larger cross sectional area of the bone was positively correlated with larger bone diameters ($P \leq 0.01$). Compressive stress was significantly lower in case of larger bone diameters ($P \leq 0.01$). As opposed to the bending force, compressive force and compressive stress were positively correlated with bone wall thickness on the lateral plane ($P \leq 0.05$).

Table 6 presents the correlations between traits characterizing the bending and compressive strength of the bone and the mineralization degree, established by the ash, Ca, P and Mg content and the Ca : P ratio. Significant correlations were identified between section moduli of the bone and the Ca content and Ca : P ratio ($P \leq 0.01$). These indicate a negative correlation between the calcium content in the bone tissue and the sectional area of the bone ($P \leq 0.01$). Significant positive correlations were established between the Ca content in the bone tissue and the bending stress value σ_g ($P \leq 0.01$), which might suggest larger bending strength of bones containing more calcium in the structure of their tissue.

Table 6. Overall correlation coefficients between bone mineral content and bone strength at bending and stress characteristics, (n = 53)
Tabela 6. Współczynniki korelacji ogólnej między cechami wytrzymałości a składem mineralnym kości, (n = 53)

Correlations - Korelacje	Ash Popiół	Ca	P	Ca : P	Mg
Bending force P, kN Siła zginająca P, kN	.10	-.27	.10	-.26	-.01
Bending moment M_{gmax}, Nm Moment gnący, M_{gmax}, Nm	.10	-.27	.10	-.26	-.01
Section modulus W_x, mm^2 Wskaźnik przekroju W_x, mm^2	.02	-.58^{xx}	.21	-.56^{xx}	.17
Bending stress σ_g, MPa Naprężenie zginające σ_g, MPa	.06	.42^{xx}	-.17	.42^{xx}	-.18
Stress force P_{max}, kN Siła ściskająca P_{max}, kN	.28^{x}	-.09	.19	-.17	-.22
Cross sectional area F, mm^2 Pole przekroju F, mm^2	.06	-.49^{xx}	.03	-.48^{xx}	.14
Compressive stress σ_c, MPa Naprężenie ściskające σ_c, MPa	.19	.26	.01	.20	-.30^{x}

x – P ≤ 0.05
xx – P ≤ 0.01

CONCLUSIONS

Analysis of relations between the geometry of long bones, their outside and inside diameters, thickness of the bone shaft wall and the bending and compressive strength as well as the mineralization degree established by the calcium content in the bone tissue leads to the following conclusions:

The bending and breaking strength of the bone increased with the cross section diameters.

The compressive strength of the bone increased with the thickness of the bone shaft wall and the degree of bone mineralization determined by calcium content and higher calcium-phosphorous ratio.

The groups of pigs subject to the study differed significantly in terms of mechanical strength properties. The bones of the ZŁP breed demonstrated lower resistance to bending loads and larger resistance to compressive loads than the bones of the PLW x PL crossbreds. Larger tibial bones of the crossbreds resulted in increased resistance to bending loads causing mechanical fractures. Consequently, the results of this study show that intensive genetic improvement towards elevated musculature levels in pigs does not necessarily entail weakening of the skeletal structure or resistance to mechanical stress.

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