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Comparative study of the mechanical properties, micro-structure, and composition of the cranial and beak bones of the great spotted woodpecker and the lark bird

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Woodpeckers are well able to resist head injury during repeated high speed impacts at 6–7 m s^{-1} with decelerations up to 1000 g. This study was designed to compare the mechanical properties, microstructures and compositions of cranial bone and beak bone of great spotted woodpecker (*Dendrocopos major*) and the Mongolian sky lark (*Melanocorypha mongolica*). Microstructures were observed using micro-computed tomography and scanning electron microscopy and their compositions were characterized by X-ray powder diffraction and Fourier-transform infrared spectroscopy. Under high stress, the cranial bone and the beak of the woodpecker exhibited distinctive mechanical features, which were associated with differences in micro-structure and composition, compared with those of the lark. Evolutionary optimization of bone micro-structure has enabled functional adaptation to the woodpecker's specific lifestyle. Its characteristic micro-structure efficiently avoids head impact injury and may provide potential clues to the prevention of brain injury using bio-inspired designs of shock-absorbing materials.

woodpecker, head, mechanical property, micro-structure, composition

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Woodpeckers represent prime examples of adaptive evolution by natural selection. "The feet, tails, beaks and tongues" of these birds are admirably adapted capturing insects under the bark of trees [1]. Most woodpeckers display remarkable features that allow them to drill holes in solid, unrotten wood at impact speeds of 6–7 m s^{-1}, and with deceleration forces of 1000 g, without experiencing head injury [2,3]. Over the years, woodpeckers have been considered a testament to the superiority of bioengineering design. Free-body analysis has shown that compressive shocks acting on the bill do not travel directly into the brain case to the brain [4]. Other proposed adaptive mechanisms include particular types of motion, body functions, and special micro-structures [3,5,6]. The shape of the bill is adapted to the forces on it during drilling [7], and *in vivo* bite force is reflected in skull morphology and geometry, and in the capacity for contraction of the jaw muscles [8,9]. The woodpecker's brain is tightly packed with relatively dense yet spongy bone, particularly in the occiput, which is located in the "contre-coup" position relative to the beak [10,11].

Biomaterials in nature frequently exhibit highly complex and elegant mechanisms for self-assembly and nanofabrication that have been designed by natural evolution over millions of years [12]. There is also overwhelming evidence that the mineral mass and micro-structure of bone are susceptible to stimulation by mechanical loads, ensuring that

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its mechanical behavior and strength are adapted to environmental changes [13–17]. However, there have been few systematic analyses of these properties of woodpecker's skull. To understand how woodpeckers are adapted to pecking at high-speeds and frequency, we carried out a comparison study concerning mechanical properties, micro-structure, composition of cranial bone and beak between the great spotted woodpecker and the lark, a bird that does not exhibit this behavior. We hypothesized that, relative to the lark, the woodpecker's skull would demonstrate superior mechanical properties, micro-structures and a composition adapted to their high-speed and high-frequency drumming behavior. The observations reported below support this hypothesis.

1 Materials and methods

1.1 Subjects and specimens

The woodpecker investigated here was the great spotted woodpecker (*Dendrocopos major*), which is widely distributed in Northern China. It has a body length of 21 cm and weights 70 g. The Mongolian sky lark (*Melanocorypha mongolica*), which is a song bird of comparable size and weight (20 cm, 65 g) was selected as a control. Great spotted woodpeckers tap regularly and efficiently, whereas larks do not tap or drum. Dead specimens of a woodpecker and a lark were collected from bird feeders for the micro-parameters measurements and composition analyses. Twelve cranial and 12 beak samples measuring 4 mm × 4 mm were cut from the woodpecker and the lark bird, respectively, as indicated in Figure 1.

1.2 Mechanical tests

Destructive mechanical compression tests were carried out on the cranial bone and beak samples using a material testing system (Autography Series, Shimadzu Corporation, Japan) using 50 N and 1 kN load cells respectively, at room temperature (~22°C) and humidity (~65%). Briefly, each specimen was placed between two steel rods lubricated with low-viscosity mineral oil to ensure low friction. The direction of the compressive load is shown in Figure 1. After pre-conditioning, the specimen was compressed at a constant strain rate 0.002 s^{-1}, until a shortening of 3% was reached [18]. Young's modulus was calculated from the linear portion of the recorded stress-strain curve below the ultimate strength represented by the tangent of the stress-strain curve at a strain of 0.6% [19].

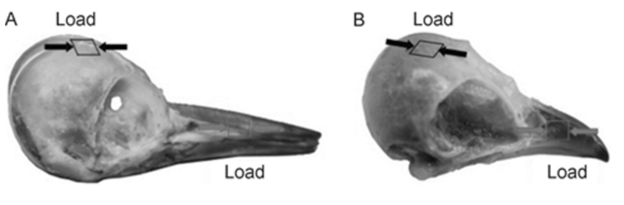

Figure 1 Skulls of great spotted woodpecker (A) and lark (B) showing the location of samples and the direction of the load during testing.

1.3 Micro-parameter measurements

The micro-parameters of cranial bone and beak bone were measured three-dimensionally by micro-computed non-destructive tomography (micro-CT, Skyscan1076, Skyscan, Belgium) at a spatial resolution of 35 μm. The micro-structure of the specimens was observed by scanning electron microscopy (SEM, JSM-6490, JEOL, Tokyo, Japan) at an accelerating voltage of 10 kV and a working distance of 10–15 mm, at room temperature. Specimens were washed with normal saline to remove blood, mucus and tissue fluid, dehydrated in an ascending ethanol series (30% to 100%) for 20 min at each concentration, and then sputter-coated with an approximately 20 nm-layer of gold before observation. Values are presented as means and standard deviation (SD). Differences between the cranial bone and beak of the woodpecker and the lark were analyzed using paired student's *t*-tests (SPSS version16, Chicago, IL, USA), with $P<0.05$ accepted as significant. All reported *P*-values are two-sided.

1.4 Composition analysis

The phase composition of the samples after calcinations in air at 600°C for 12 h was characterized using X-ray powder diffraction (XRD, Bruker D8 Advance, Bruker AXS GmbH, Karlsruhe, Germany) and Fourier-transform infrared spectroscopy (FTIR, Magna-IR 760, Nicolet, Minneapolis, USA). XRD was carried out with a scanning step of $2\theta=0.02°$. FTIR was carried out in the wave number range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} using KBr pellets.

2 Results

2.1 Mechanical properties

Descriptive statistics of the mechanical properties of the cranial bone and beak of the woodpecker and the lark are presented in Table 1. The Young's modulus and ultimate strength of the cranial bones of the woodpecker were significantly higher than those of the lark ($P<0.001$); however, there were no significant differences in the mechanical parameters of their beaks. The cranial bone of woodpecker had an initial Young's modulus of (306.50±19.42) MPa and an ultimate strength of (6.38±0.29) MPa at ~3% strain, at which point the bone started to break.

2.2 Micro-structural parameters

The microstructural parameters of the cranial bone and

Table 1 Mechanical properties of the cranial bone and beak of the great spotted woodpecker and the lark[a)]

	Cranial bone				Beak			
	Woodpecker		Lark		Woodpecker		Lark	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E-modulus (MPa)	306.50	19.42	3.10**	0.61	930	79	1018	83
Ultimate strength (MPa)	6.38	0.29	0.55**	0.14	21	5.1	26	5.5
Ultimate strain (%)	3.30	0.12	3.71	0.15	5.53	0.19	4.22	0.19

a) **, Statistically significant difference between woodpecker and lark (P<0.001).

beaks of the great spotted woodpecker and the lark based on the micro-CT images are presented in Table 2. The structural model index (SMI) for the cranial bone of woodpecker was lower than that of lark (P<0.001), and the trabecular thickness (Tb.Th), the trabecular number (Tb.N) were higher in the woodpecker (P<0.001). For the beak, the SMI (P <0.001), Tb.N (P<0.05), and bone mineral density (BMD) (P<0.001) in woodpecker were all significantly higher, and the Tb.Th (P<0.05) was lower.

2.3 Composition

Figures 2 and 3 show the XRD patterns and FTIR spectra, respectively, of the calcined samples. The principal phase component of all samples of both birds was identified as calcium-deficient carbonate-hydroxylapatite, despite a variation of about 0.3° in the angle 2θ. In addition to the carbonate-hydroxylapatite peak at 2θ=37°, unknown phase peaks appeared in the XRD pattern. These samples had low crystallinity and a high baseline, indicating the presence of amorphous crystals despite heat-treatment at 600°C for 12 h. As shown in Figure 3, the bands at 1094, 1038, 963, 602 and 563 cm^{-1} were assigned to the stretching and bending motions of the phosphate groups in hydroxyapatite, and the bands at 3571 and 633 cm^{-1} were assigned to the stretching modes of the hydroxyl groups. These were clearly visible in the FTIR spectra [20]. It was similar in each. On the other hand, the bands at 1421 and 1457 cm^{-1} were attributed to the CO_3^{2-} group. The symmetrical stretching vibration band of the HPO_4^{2-} group at 872 cm^{-1} also appeared in the spectra [21]. Thus, the unknown XRD peaks were speculated to be other forms of calcium phosphate.

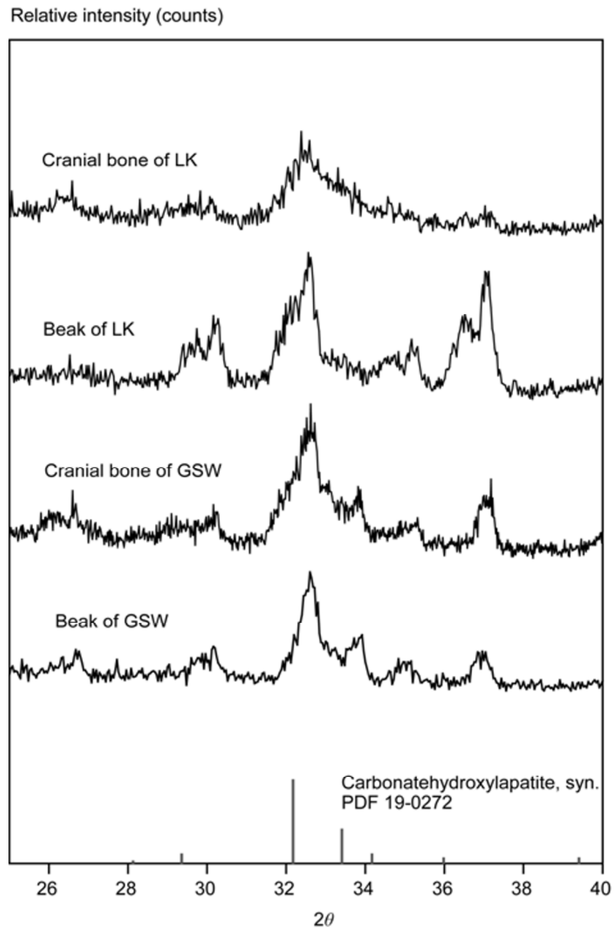

Figure 2 XRD patterns of bone and beak samples calcined at 600°C for 12 h (GSW, great spotted woodpecker; LK, lark).

Table 2 Micro-parameters of the cranial bone and the beak of the great spotted woodpecker and the lark

	Cranial bone				Beak			
	Woodpecker		Lark		Woodpecker		Lark	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Structural model index (SMI)	1.194	0.311	2.772**	0.213	2.236	0.157	0.245**	0.012
Trabecular thickness (Tb.Th; mm)	0.190	0.018	0.076**	0.009	0.241	0.008	0.346*	0.005
Trabecular number (Tb.N; 1 mm^{-1})	0.506	0.123	0.313**	0.085	2.465	0.187	1.946*	0.116
Trabecular separation (Tb.Sp; mm)	0.451	0.286	0.774*	0.169	0.198	0.025	0.208	0.043
Bone mineral density (BMD; g cm^{-3})	0.218	0.015	0.155*	0.021	0.086	0.006	0.014**	0.003

a) Statistically significant difference between woodpecker and lark: *, P<0.05; **, P<0.001.

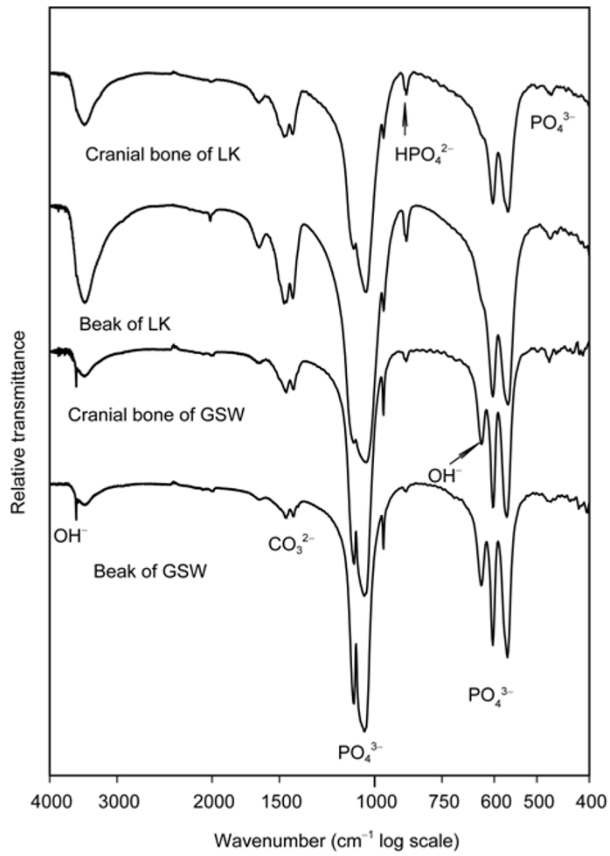

Figure 3 FTIR spectra of cranial bone and beak samples calcined at 600°C for 12 h.

3 Discussion

The mechanical strength of bone is determined by the microstructure and the composition of the bone tissue [22,23]. Therefore, the present comparison of the mechanical properties, microstructure and composition of the cranial and beak bone of the two birds (Tables 1 and 2) allows us to better understand how the woodpecker avoids impact injury to the head. Among the mechanical parameters analyzed, the ultimate strength (σ_u) represents the property of the bone at the point of fracture [24]. Thus, it is noteworthy that the ultimate strength of woodpecker's cranial bone was markedly higher than that of the lark. In contrast, there was no significant difference between the two birds in the ultimate strengths of their beaks.

The profile of the woodpecker skull in the coronal plane was nearly ellipsoidal and smoother than that of the lark (Figure 4A and B). Additionally, the woodpecker brain was more tightly packed in the cranium, which consisted of relatively dense and less spongy bone than that of the lark (Figures 5–7). More plate-like spongy bones were observed in cranial bone of woodpecker, while more rod-like structures were present in the cranium of the lark. The SMI parameter was introduced to quantify the characteristic form of three-dimensional structures in terms of the quantity of plate-like and rod-like structures. For ideal plate and rod structures, the SMI values are 0 and 3, respectively, and are independent of their physical dimensions. For a structure with both plates and rods of equal thickness, the value lies between 0 and 3, depending on the volume ratio of the rods and plates. Here, the woodpecker's cranial bone (SMI=1.194) had more plate-like structures than the lark (SMI= 2.772). In contrast, the beak of the woodpecker was more rod-like (SMI=2.236). These observations were consistent with their appearance by SEM (Figure 5A and B). The SMI values do not provide accurate information on trabecular bone which needs to be complemented with measurement of the thickness, number and spacing of the trabecular (Tb.Th, Tb.N and Tb.Sp, respectively). These values directly quantify the structure within a three-dimensional region of interest (3-D ROI) and have also been correlated with the ultimate strength of bone [25]. The cranial bone of the woodpecker had a greater thickness and number of individual

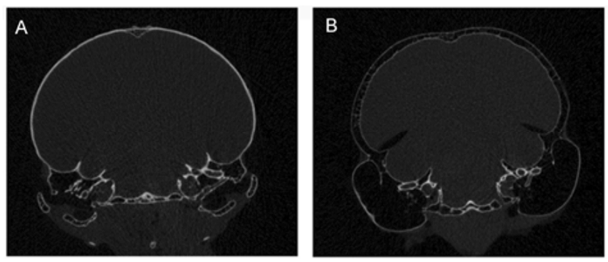

Figure 4 Micro-CT images of heads of great spotted woodpecker (A) and lark (B).

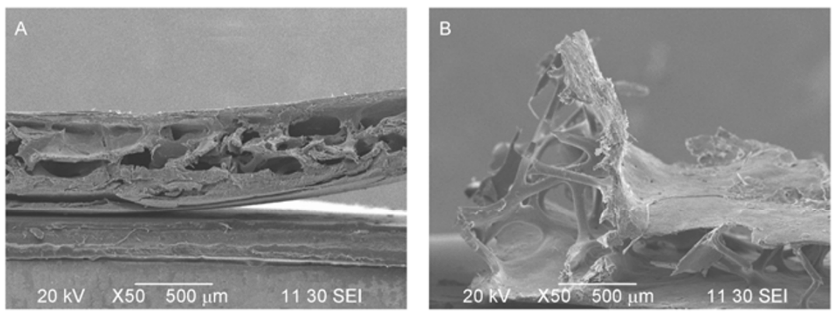

Figure 5 SEM images of cranial bone of great spotted woodpecker (A) and lark (B).

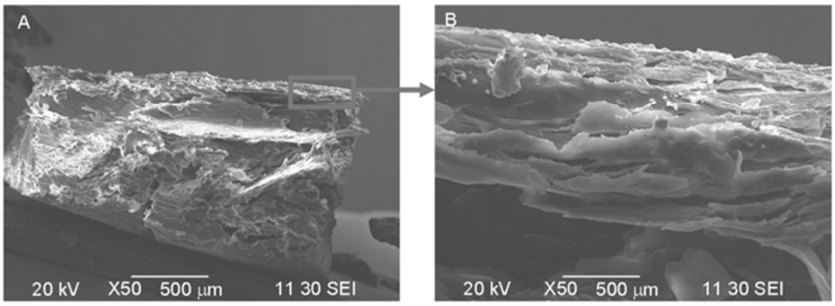

Figure 6 SEM images of great spotted woodpecker beak.

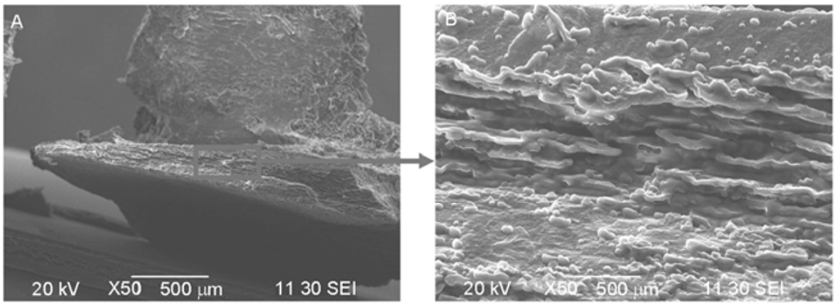

Figure 7 SEM images of lark bird's beak.

trabeculae, which were more closely spaced and more plate-like trabecular than in lark. These features combined to confer a higher ultimate strength to the sample from the woodpecker. For the beak, the samples from woodpecker had more rod-like structures of greater thickness, and fewer trabeculae than the lark.

Thus, it appears that the mechanical properties and microstructure are closely related to each other. More plate-like structures, greater thickness and numbers of trabeculae, and closer spacing between individual trabeculae in the woodpecker cranial bone may lead to less deformation during pecking, which would decrease the stress on the brain. Conversely, the greater quantity of rod-like structures and thinner trabeculae of the woodpecker's beak may lead to larger deformation during impact forces. Although there was no significant difference between the woodpecker and the lark in the spacing of individual trabeculae within 3-D ROI of the beak, the greater trabecular number in the woodpecker would contribute to improving its ultimate strength. As the impact load is primarily absorbed and distributed by the beak, its transmission to the brain would be decreased. Together these parameters combined to produce quite similar ultimate strengths of the beaks of the woodpecker and the lark. This suggests that the mechanical properties were sensitive to the shape of individual trabeculae.

Samples with higher contents of organic matter experience greater material loss on ignition. Materials that contain more organic material are expected to exhibit greater flexibility under load. The ignition losses of the cranial and beak bones of the woodpecker after calcinations at 600°C for 12 h were 47.75% and 31.84%, respectively; for the lark, they were 57.20% and 15.43%, respectively. Both cranial bones had higher ignition losses than the beak bones, indicating that the proportions of bone mineral in the cranial bones were less than beak bones. The higher ignition loss in the beak bone of woodpecker also implies a greater deformation may occur under impact stress. Thus, the applied impact stress could be partially absorbed by the beak bone and before transmission to the cranial bone.

We conclude that, compared with the lark, the cranial bone of the woodpecker achieves a higher ultimate strength and resistance to impact injury as a result of its unique microstructure, including more plate-like trabecular bone, greater thickness, greater numbers, and closer spacing of trabeculae, and a higher proportion of bone mineral. These distinctive mechanical properties, microstructure and composition of the woodpecker's cranial bone and beak provide an excellent resistance to head impact injury at a high speed and deceleration. Such information may perhaps inspire the design and optimization of protective headgear for humans.

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