

A BIOMECHANICAL STUDY OF VERTEBRAL ALLOMETRY IN PRIMATES

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INTRODUCTION

Comparative analysis of the skeleton is fundamental to the study of human evolution. Although many studies have examined the relationship between bone size/biomechanics and animal body weight in the long bones (McMahon 1975, Selker 1989), little is known regarding allometry in the spine. Our overall goal is to understand biomechanical variation in the spine among species. In this study, we determine **1**) how vertebral bone strength (as evaluated from measures of structural rigidity) varies with body weight among primates, and **2**) how mechanical efficiency (represented by the ratio of bone strength to bone mass) of vertebrae varies among primates.

METHODS

Adult thoracic (T8) vertebral specimens were selected from four species: human (*Homo sapien*), gorilla (*Gorilla gorilla*), chimpanzee (*Pan troglodyte*), and gibbon (*Hylobates lar*) (n=10 per species; 5 female, 5 male). All specimens were obtained from the Hamann-Todd osteological collection at the Cleveland Museum of Natural History. Human specimens ranged in age at death from 23-40 (31.7 ± 5.9 , mean \pm SD). Non-human primate specimens were skeletally mature. Body weight for human, gorilla, and chimpanzee specimens was determined from measures of femoral head volume (Ruff 1988). Body weight for gibbons was

determined from femoral head diameter (McHenry 1992).

QCT scans were obtained for biomechanical analysis. Vertebrae were submerged in a 20% ethanol solution and placed under a vacuum to remove air bubbles. Axial scans were performed on a Siemens Somatom Sensation 16 QCT scanning machine (140kV, 120mA, 0.75mm slice thickness). A liquid K₂HPO₄ mineral content calibration phantom was used to determine density per voxel (ρ_{QCT} , mg/cm³). Volumetric bone mineral density (vBMD) was computed for each vertebral body including endplates and cortex. Total bone mineral content (BMC) of the vertebral body was used as a measure of bone mass.

Structural rigidity was used as an assay of bone strength. The elastic modulus of each voxel was determined from published relationships between ρ_{QCT} , ash density, and elastic modulus (Keyak 1994, Keller 1994). The axial and anteroposterior bending rigidity of each transverse slice of the vertebra was calculated using composite beam theory (Whealan 2000, Crawford 2004). The minimum values of rigidity in each loading mode were used as indicators of bone strength, S_{axial} and $S_{bending}$. Mechanical efficiency was evaluated as the ratio of strength to bone mass (S_{axial}/BMC and $S_{bending}/BMC$, Hernandez 2006).

RESULTS AND DISCUSSION

Animal body weight spanned two orders of magnitude (6-201 kg). The axial strength increased linearly with body weight ($r^2=0.82$, $p<0.001$, Figure 1). Bending strength also increased with body weight following a power-law relationship with an exponent of 1.5 ($r^2=0.95$, $p<0.001$). Mechanical efficiency in axial compression (S_{axial}/BMC) was found to be smaller in animals with larger body weight ($r^2=0.56$, $p<0.001$, Figure 2). Conversely, mechanical efficiency in bending ($S_{bending}/BMC$) increased with body weight following a power-law relationship ($r^2=0.82$, $p<0.001$).

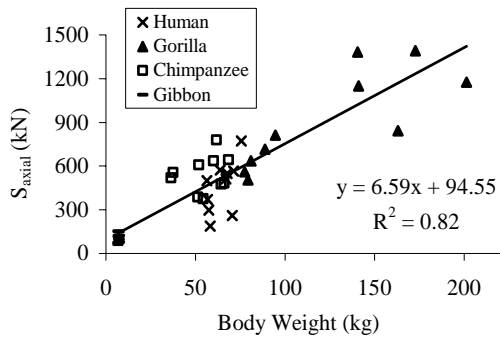


Figure 1: Strength in axial compression follows a linear relationship with body weight in human and non-human primates.

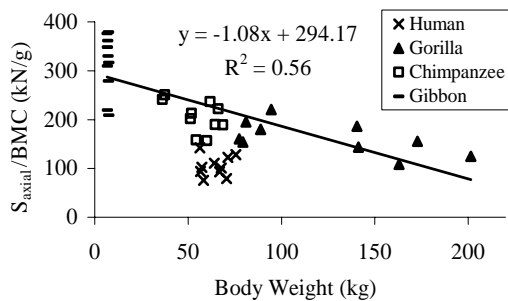


Figure 2: Mechanical efficiency in axial compression was reduced in larger animals.

In humans, mechanical efficiency in axial loading was reduced compared to non-human primates with similar body weight

($p<0.001$). The volumetric bone mineral density of human vertebra was significantly less than that in non-human primates ($p<0.001$).

SUMMARY/CONCLUSIONS

Allometric relationships are useful for accounting for differences in size while comparing species. In this study we determined the allometric relationships between vertebral bone strength and body weight in human and non-human primates. Furthermore, our analysis suggests that as primates increase in size, vertebral bone mass is utilized more efficiently in bending, but less efficiently in axial compression. The reduction in axial mechanical efficiency appears to be more pronounced in humans than in other primates of similar body weight, potentially because humans show reduced overall volumetric bone mineral density. Reduced bone density and mechanical efficiency in axial loading may help to explain why humans are susceptible to age related fractures in the spine, which are not observed in other primates.

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