A STUDY ON CERVICAL SPINE OF GIRAFFE TO CONSIDER ITS MECHANICAL ADAPTATION

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SUMMARY
Mechanical strength of giraffe's neck and its mechanical optimality was investigated in this study. Finite-element analysis of cervical spine of giraffe was carried out. It was observed that material inhomogeneity of bone was effective to be reduced stress of cervical vertebrae. Minimum volume design problem with stress constraints was considered for the hourglass-shape column corresponded to cervical vertebra of giraffe. It was suggested the concave shape of the cervical vertebrae was explicable by mechanical optimality.

INTRODUCTION
Head and neck of giraffe sometimes reaches 2.5m long and weighs 150kg [1]. Such long and heavy neck of giraffe is subjected to large moment and force. Giraffe can swing the neck flexibly in spite of the severe mechanical condition. So, mechanical adaptation is expected on musculoskeletal structure of giraffe's neck. Several anatomical studies of musculoskeletal system of giraffe's neck have been reported [2, 3], however, there was no biomechanical study. Purpose of this study is to evaluate the mechanical strength of giraffe's neck and to consider its mechanical adaptation.

METHODS
We created the finite-element model based on CT images taken from the skeletal specimen of giraffe owned by the Osaka Museum of Natural History (Figure.1). The cervical spine model was composed of skull, all cervical vertebrae, 1st and 2nd thoracic vertebra, vertebral disks and nuchal ligaments as shown in figure 2. Inhomogeneous material properties of vertebrae were given due to bone mass density obtained from CT value (Figure 3). Material properties of vertebral disks and nuchal ligaments were assumed by using other animal data of past literature. Horizontally extending posture was considered because largest moment was loaded. Alignment of the vertebrae in the model was determined by referring anatomical charts of giraffe and other mammals. Gravity loads correspond to the mass of head and each vertebra levels were applied. Mass of head and neck were assumed as 20Kg and 70Kg. The mass of neck was divided into each vertebra levels in according to their length. Posterior end of the 2nd thoracic vertebra (T2) was fixed, and the ligament was fixed at insertion point of spinous process of T2.

FE analyses were performed for two cases in order to ensure influence of bone inhomogeneity. One was homogeneous bone case (case 1) and the other was inhomogeneous bone case (case 2). In case 1, average of bone densities were given separately for cortical shell and solid of the vertebrae.

Then, we focused on particular shape of the vertebral body. The shape of cervical vertebral body of giraffe is hourglass (narrow in the middle) as shown in figure 3. It looks more like long bone, such as femur or tibia, than cervical vertebra of other mammals. A shape optimization problem was considered in which objective was volume to be minimizing under stress constraint of bone and intervertebral disc for a simplified beam model simulating a cervical vertebral body. Axial compressive load and bending moment was applied. Design variables were diameters of circular cross-section of the beam model in the middle and end.

Figure 1: Bone specimen of giraffe neck (from the Osaka Museum of Natural History).

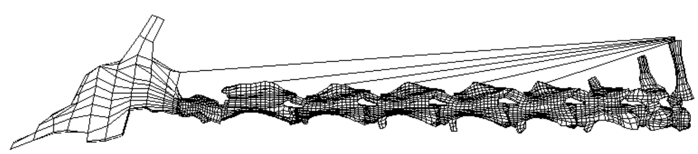

Figure 2: Finite-element model of cervical spine of giraffe.

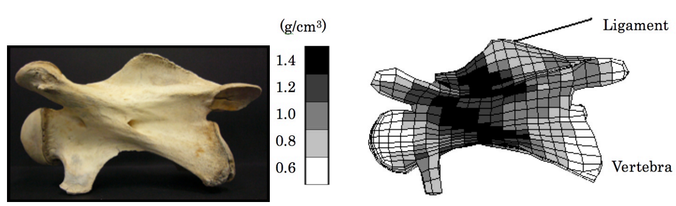

Figure 3: Sample of 5th cervical vertebra (left) and density distribution of 5th cervical vertebra (right) in lateral view.

RESULTS AND DISCUSSION
In the finite-element analysis, as shown in table 1, maximum tensile principal stresses of inhomogeneous case (case 2) were totally lower than homogeneous bone case (case 1) especially

for C5 and C7. Belt-like high-density area at central part of C5 is effective to reduce large tensile principal stress occurred at anterior side, because nuchal ligament force is supported by the high-density area.

The cervical vertebral body was simplified to hourglass-shape column under compressive axial load and bending moment to obtain stress of bone by using classical beam theory. Figure 4 shows the simple column model of the vertebral body, where d_i, A_i and Z_i is diameter, cress-sectional area and section modulus of cross-section of the column, respectively. Subscript 1 and 2 denote end section and center section. Circular cross-section of the column was assumed here. F is compressive load in axial direction and M is bending moment.

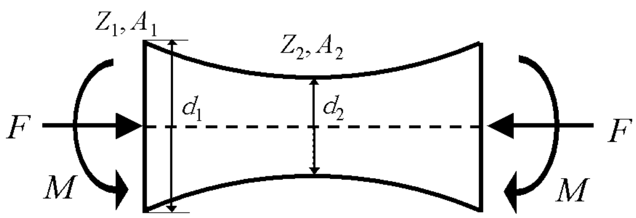

Figure 4: Simple column model of the vertebral body of cervical spine of giraffe and its loading condition

Figure 5 shows the shape index (d_2 / d_1) of the column with changing bending moment ratio to compressive load from 0 to 2 obtained by solving the minimum volume design problem. The optimum shape of the beam model corresponded well to hourglass shape of the vertebral body. It was suggested the hourglass shape of giraffe's cervical vertebra was one of mechanical adaptation to the long neck.

CONCLUSIONS

Finite-element models of giraffe's neck structure has horizontally extending posture were created based on CT images, and stress analyses were carried out. In the results, we clarified that inhomogeneity of bone was effective to be reduced tensile stress at anterior side of cervical vertebrae.
Minimum volume design problem with stress constraints was formulated for the hourglass-shape column, which was simplified from vertebral body of giraffe cervical spine, under axial compressive load and bending moment. It was obvious that the concave shape of the vertebral body was one of optimal shape, which provides minimum volume satisfying stress constraints of bone and intervertebral disk. It was suggested the unique shape of the cervical vertebrae of giraffe was explicable by mechanical optimality.

REFERENCES

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Table 1: Maximum value of displacement, ligament stress, tensile and compressive principal stress of bone

Maximum Value	Displacement (m)	Stress of ligament (MPa)	Tensile principal stress of bone (MPa)	Compressive principal stress of bone (MPa)
Case 1	0.39	0.53	8.5	13.4
Case 2	0.40	0.54	8.0	14.3

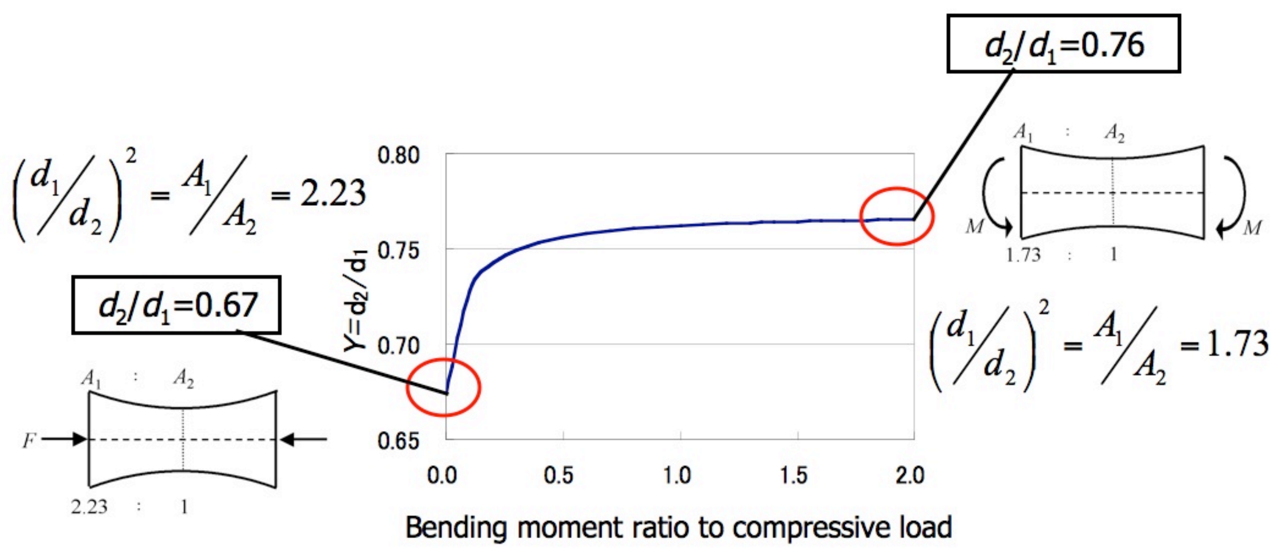

Figure 5: Shape index vs. bending moment ratio to compressive load in solution of minimum volume design problem of simple column model of cervical vertebral body of giraffe.