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Finite Element Analysis of the Femur of Japanese Quail (*Coturnix coturnix japonica*)

Análisis por Elementos Finitos del Fémur de Codorniz Japonesa (*Coturnix coturnix japonica*)

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SUMMARY: The biomechanical performance of limb bones is useful to reflect an animal's adaptation to external loads and behaviors. In this study, we used the finite element method to simulate the load acting on the intact femur of the Japanese quails (*Coturnix coturnix* japonica) in the context of terrestrial locomotion and take-off for flight, in order to explore the functional significance of the femoral form and limb postures. It is shown that the distribution of stress was similar in all cases, furthermore, the lower 2/3 of the dorsal and ventral region of the femur suffered higher stress, and the junction between the distal diaphysis and the medial condyle was the most vulnerable area. The stress reaches its highest value under the condition of about 90-100 degrees of loading angle; when this angle is larger than 110 degrees, the femur will be relatively safe. These findings suggested that quail femur is more suitable to terrestrial locomotion than take-off. This kind of work will contribute to revealing the locomotor behavior of fossil taxa.

KEY WORDS: Quail; Femur; Finite element analysis; Stress.

INTRODUCTION

The form-function relationships of the skeletons are of great interest to zoological and paleontological studies (Ross, 2005; Benton, 2010). Bone is a dynamic structure capable of modifying its size, shape, and biology in response to external mechanical requirements (Rayfield, 2007). Differences in habitat or life habits cause animals to experience various external loads. As a result, analysis of the mechanical performance of an animal's bones can shed light on its adaptation to its environment.

Birds are the most taxonomically diverse of all tetrapod vertebrates and display a great diversity in life habits and global distribution (Abourachid & Höfling, 2012). The functional diversity of their hind limbs has helped birds colonize every environment on the planet (Abourachid & Höfling). Birds rely on their hind limbs to support their bodies, for momentum during terrestrial locomotion, and to provide most of the initial velocity required to become airborne during take-off. To perform these functions effectively, the hind limbs must have sufficient strength and stiffness. Several studies showed that there are large variations in long bone morphology among bird species, indicating possible adaptations that reflect different behaviors (Gatesy & Middleton, 1997; Zeffer *et al*., 2003).

The biomechanical performance of long bones is influenced by element size, element shape, loading conditions, and material properties (Beaupré & Carter, 1992; Erickson *et al*., 2002). The small size of the femur in many bird species makes it difficult to investigate its mechanical properties using traditional mechanical tests. Due to the diverse and complex forms of bones, it is hard to reveal their stress conditions by engineering formulae. Furthermore, some parts of bones are hard to reach to implant strain gauges. The finite element (FE) method effectively solves these problems due to its abilities to handle complex stress analyses (Ross). It allows individual parameters to be varied while others are kept constant which is difficult to achieve with experimental methods.

In this study, we used FE method to simulate the loads acting on the femur of the Japanese quails (*Coturnix coturnix japonica*) during both terrestrial locomotion and take-off to explore the functional significance of the femoral shapes and postures. The Japanese quail is a typical ground-dwelling bird that prefers to run rather than fly from danger (Johnsgard, 1988). Its hindlimb proportion is similar to non-avian theropods whose hindlimb is primary designed for terrestrial bipedalism (Gatesy & Middleton). By analyzing

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the stress conditions of the femurs, we determined the mechanical performance and identified certain features of the femurs that are likely to be suitable to the quails' environment and behavior. This type of analysis has great potential for investigating the locomotor behavior of fossil taxa in paleontological studies (Rayfield).

MATERIAL AND METHOD

Three healthy mature Japanese quails (mean weight: 155.2 g, range 151.83–159.30 g) were collected from a commercial quail farm in Beijing. Three right femurs were dissected after the birds were sacrificed. The project was approved by the Animal Care and Ethics Committee of Capital Normal University. After that, samples were frozen by wrapping them in gauze and placing them in saline solution in a freezer at -20 °C.

Femurs were scanned at a resolution of 20 mm with a Skyscan model 1076 micro CT scanner. A three-dimensional reconstruction was performed using Mimics 16.0 software, and then the 3D models were converted into NURBS-based solid models using the reverse engineering software Geomagic Studio. The NURBS-based solid models were imported into ABAQUS 6.14 for subsequent analysis. We primarily concerned with the distribution of stress and pattern of variation in stress magnitude of femur under the physiologic loads. Both structural and material properties have effects on bone stress conditions (Erickson *et al*.). The size and shape of a bone are shown to be the primary variables in determining bone strength, and functional demands on vertebrate long bone can be satisfied predominantly through changes in bone geometry while material properties generally keep constant (Biewener, 1982; Selker & Carter, 1989; Erickson *et al*.). Therefore, we ignored potential differences in material properties, treated the femur as a homogenous isotropic material in the experiment. Young's modulus for the quail femur models was defined as 22.4 GPa which is the average of long bones of birds and mammals (Erickson *et al*.). The Poisson's ratio we used here is 0.3 which derived from the literature (Kupczik *et al*., 2007).

The load arms of bending moments that femurs must resist are in proportion to the femoral length, whereas the bending load is in proportion to body mass (Selker & Carter; Habib & Ruff, 2008). In addition, the quail femur moves almost exclusively in the sagittal plane during locomotion (Gatesy & Biewener, 1991; Gatesy, 1999; Abourachid *et al*., 2011). Therefore, in finite element analysis, we applied loads on the femoral head, and constrained the surface of the distal epiphysis. In order to apply the load on the surface of femoral head evenly, we chose a reference point on the femoral head and coupled it with the target surface. Load was then applied on the reference point. The angle of the force applied to the femur was defined as the angle between the long axis of the femur and the direction of loading applied to the femoral head (Fig. 1A).

When quails take off for flight, the angle of loading that applied to the femur is, on average, between 80 and 130 degrees (Earls, 2000). However, during terrestrial locomotion, the movement of the femur is much more restricted and the femur moves less than 10 degrees at the hip in the stance phase (Gatesy & Biewener). Take the orientation of ground reaction force in to account, the loading angles are approximately between 120 to 150 degrees during the single support phase period of terrestrial locomotion (Clark & Alexander, 1975; Abourachid *et al*.). With respect to both take-off and walking, loads have been applied to femurs from eight angles which are 80, 90, 100, 110, 120, 130, 140, and 150 degrees (Fig. 1A).

Quail legs experience a force of about 3.9 times their body weight on landing when they jump over a 15-cm-high barrier (Clark & Alexander). Likewise, during take-off, a quail must exert sufficient pressure on the ground to overcome gravity, which can reach a maximum of about 8 times its body weight (Earls). Therefore, the load acting on a single hindlimb is either twice or four times the animals' body weight. Here we used a load of four times the body weight, which is an average loading value of 6 N (gravity plus acceleration = 9.8 m/s^2).

A 10-noded tetrahedral finite element mesh with C3D10 elements was automatically generated using an advancing-front algorithm. There are about146000 elements, 243000 nodes in each model (Fig. 1B). Calculations were conducted on a dual CPU Hewlett-Packard Z820 graphics workstation, which could compute the results of a single experiment in an average time of 2 minutes.

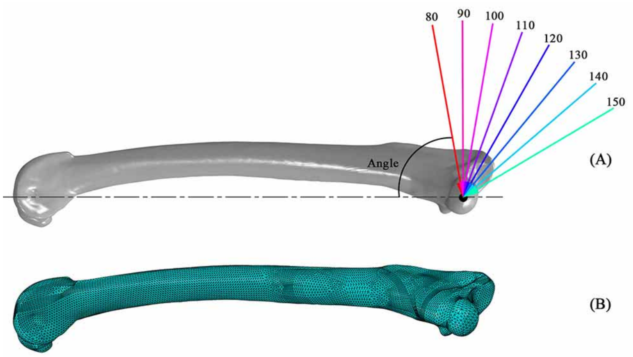

Fig. 1. Schematic illustration of the loads applied to the femur (dotted line: femoral axis, arrows: action line of force) (A); Mesh model (B).

RESULTS

The spatial arrangements of the stress are generally similar in all analyses (Fig. 2). The stress is mostly distributed in the lower 2/3 of the dorsal and ventral regions. By querying stress value, we found that the stress value increases gradually from the proximal regions to the distal parts but increases nonlinearly in the magnitude (Fig. 3). The stress increases in from about 1/3 proximal diaphysis to 1/4 distal ones of each femur, and then decreases until it reaches the diaphyseal end. At the junction between diaphysis and medial condyle, the stress increases sharply and then decreases. The regions with the highest concentration of stress, which belong to both dorsal and ventral regions of femurs 1 and 2, are all at the junction between distal diaphysis and medial condyle. But for femur 3, when the load angle ranges from 120 to 150 degrees, the maximum stress of dorsal region will be at the 1/4 distal diaphysis, whereas the maximum stress of ventral region will be at distal diaphyseal end. When the loading angle ranges from 80 to 110 degrees, the greatest stresses of both dorsal and ventral regions will be at the junction between distal diaphysis and medial condyle. Stresses in medial and lateral regions are relatively low (Fig. 2).

Regarding to the magnitude of the stress, we found that the mean value initially increases and then decreases at the middle and distal diaphysis, with the increase of loading angle (Fig. 2). The greatest stress occurs at an angle of about 90-100 degrees. When external force was loaded at the 110 to 120 degrees, stresses on the dorsal and ventral regions were nearly identical. At angles below this range, the dorsal region experienced higher stress than the ventral region, but at angles above this range, stress on the ventral region exceeded that on the dorsal region (Fig. 4).

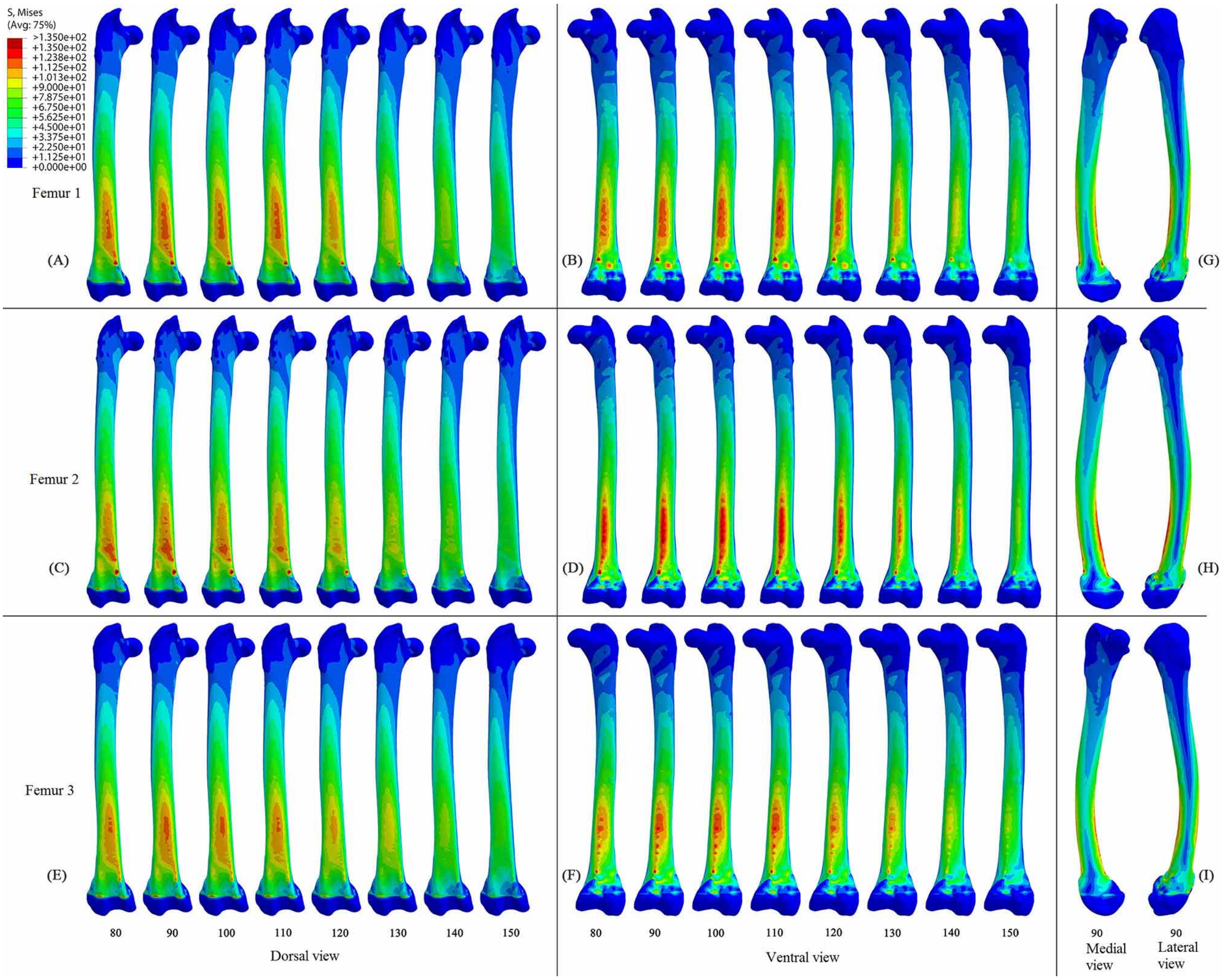

Fig. 2. Stress distribution under different loading angles.

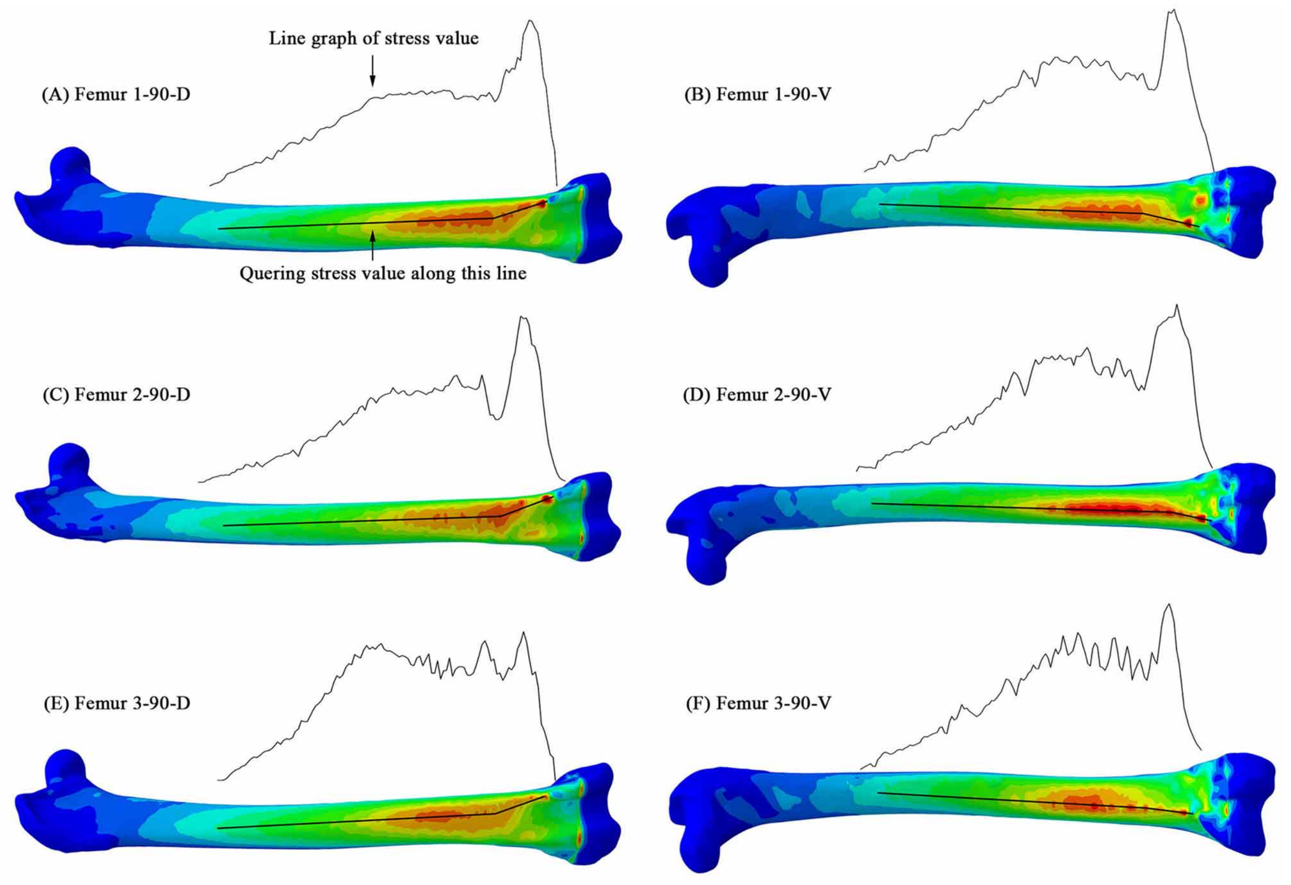

Fig. 3. Stress value along the central line of high stress region of the dorsal (D) and ventral (V) region, under the condition of a 90 degrees loading angle.

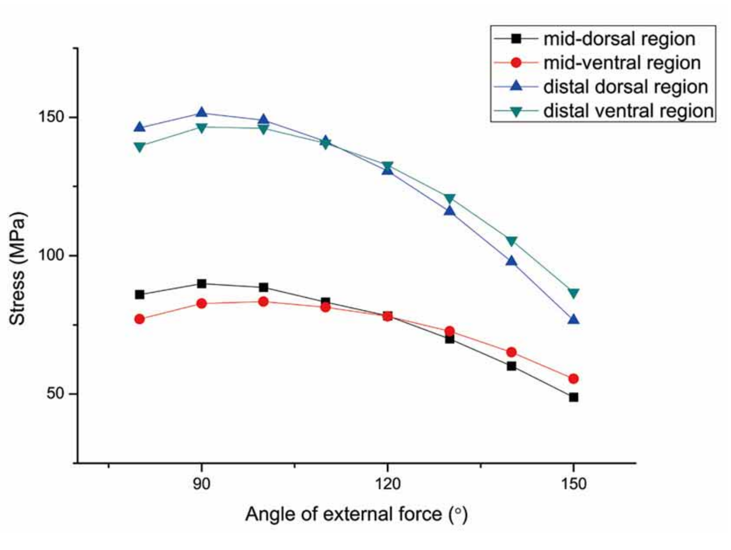

Fig. 4. Change of mean value of stress with loading angles.

DISCUSSION

This study aims to reveal the distribution and magnitude of stress of quail femur in the context of terrestrial locomotion and take-off for flight. The results indicated similar stress distribution during different locomotor activity. The junction between distal diaphysis and medial condyle was suggested to be the most vulnerable area, because of the highest concentration of stress (Fig. 3). If a quail femur breaks, the failure will be likely observed at this region first. These results are consistent with the findings of Clark & Alexander, who found that most fractures in the quail femur occurred at the distal part of the bone. Based on the fact that the distribution of stress was not uniform along the femoral shaft, and concentrated in several regions of the distal diaphysis (Fig. 3), we propose that caution should be warranted in using the engineering formulae to estimate the stress distribution of long bones;

simultaneously, the selection of regions where strain gauges are implanted will probably have some effect on the results of *in vivo* strain research.

The pattern of stress distribution on the dorsal and ventral areas indicated that the femur experiences bending deformation in response to external load. Bending causes tensile stresses and compressive stresses on the two opposite sides of bone respectively (Nordin & Frankel, 2001). When a bone is bent ventrally, the dorsal region can be under tension, while the ventral region becomes compressed (Lanyon & Baggott, 1976). Bone is more resistant to compression than to tension (Nordin & Frankel; Currey, 2002). Consequently, a decrease in tensile stress will cause an increase in safety factor (Brassey *et al*., 2013). When external force was applied beyond and larger than 110 degree, the value and decline magnitude of stress on the dorsal region was lower and more obvious, respectively, in comparison with application of force under 110 degree (Fig. 4). These results suggested that a greater loading angle corresponds to a higher safety factor, for the quail femur. During terrestrial locomotion, the loading angle acting on the femur falls within the range of 120 to 150 degrees, is greater than those of take-off (80 to 130 degrees); furthermore, with the increases of the loading angle, the femoral orientation becomes more parallel to the load, and it will cause an increasement in muscle effective mechanical advantage (Biewener, 1989, 2005). These features together make the quail femur more suitable to terrestrial locomotion than to take-off.

Finite element analysis is a useful method to investigate the mechanical performance of anatomical structures in living animals (Ross). Among extant birds, the flight modes and locomotor behaviors are quite diverse and are closely related to the morphological characteristics of limb bones. It will be interesting to do more comparative works of different birds with distinct locomotor modes. The distribution of stress on bone is also affected by muscles. The compressive forces generated in muscles contraction can in part, or completely, offset the effects of tensile stress on the femur (Nordin & Frankel). Information of muscles should be into consideration to build a more complicated model to explore the form-function relationship in the future.

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RESUMEN: El rendimiento biomecánico de los huesos de los miembros es útil para reflejar la adaptación de un animal a las cargas y comportamientos externos. En este estudio, utilizamos el método de elementos finitos para simular la carga que actúa sobre el fémur intacto de las codornices japonesas (*Coturnix coturnix* japonica) en el contexto de la locomoción terrestre y el despegue para el vuelo, con el objetivo de explorar la importancia funcional de la forma femoral y posición de los miembros. En el estudio, la distribución del estrés fue similar en todos los casos; además, los 2/3 inferiores de la región dorsal y ventral del fémur sufrieron un mayor estrés, y la unión entre la diáfisis distal y el cóndilo medial fue el área más vulnerable. La tensión alcanza su mayor valor bajo la condición de, aproximadamente, 90-100 grados de ángulo de carga; cuando este ángulo es mayor a 110 grados, el fémur esta relativamente seguro. Estos hallazgos sugieren que el fémur de codorniz es más adecuado para la locomoción terrestre que para el despegue. Este tipo de trabajo contribuirá a revelar el comportamiento locomotor de los taxones fósiles.

PALABRAS CLAVE: Codorniz; Fémur; Análisis de elementos finitos; Estrés.

REFERENCES

Abourachid, A. & Höfling, E. The legs: a key to bird evolutionary success. *J. Ornithol., 153(Suppl. 1)*:193-8, 2012.
Abourachid, A.; Hackert, R.; Herbin, M.; Libourel, P.; Lambert, F.; Gioanni, H.; Provini, P.; Blazevic, P. & Hugel, V. Bird terrestrial locomotion as revealed by 3D kinematics. *Zoology (Jena), 114(6)*:360-8, 2011.
Benton, M. J. Studying function and behavior in the fossil record. *PLoS Biol., 8(3)*:e1000321, 2010.
Biewener, A. A. Biomechanical consequences of scaling. *J. Exp. Biol., 208(Pt. 9)*:1665-76, 2005.
Biewener, A. A. Bone strength in small mammals and bipedal birds: do safety factors change with body size? *J. Exp. Biol., 98*:289-301, 1982.
Biewener, A. A. Scaling body support in mammals: limb posture and muscle mechanics. *Science, 245(4913)*:45-8, 1989.
Brassey, C. A.; Kitchener, A. C.; Withers, P. J.; Manning, P. L. & Sellers, W. I. The role of cross-sectional geometry, curvature, and limb posture in maintaining equal safety factors: a computed tomography study. *Anat. Rec. (Hoboken), 296(3)*:395-413, 2013.
Clark, J. & Alexander, R. M. Mechanics of running by quail (*Coturnix*). *J. Zool., 176(1)*:87-113, 1975.
Currey, J. D. *Bones: Structure and Mechanics.* Oxford, Princeton University Press, 2002.
Earls, K. D. Kinematics and mechanics of ground take-off in the starling Sturnis vulgaris and the quail *Coturnix coturnix*. *J. Exp. Biol., 203(Pt. 4)*:725-39, 2000.
Erickson, G. M.; Catanese, J. 3rd & Keaveny, T. M. Evolution of the biomechanical material properties of the femur. *Anat. Rec., 268(2)*:115-24, 2002.
Gatesy, S. M. & Biewener, A. A. Bipedal locomotion: effects of speed, size and limb posture in birds and humans. *J. Zool., 224(1)*:127-47, 1991.
Gatesy, S. M. & Middleton, K. M. Bipedalism, flight, and the evolution of theropod locomotor diversity. *J. Vertebr. Paleontol., 17(2)*:308-29, 1997.

Gatesy, S. M. Guineafowl hind limb function. I: Cineradiographic analysis and speed effects. *J. Morphol., 240(2)*:115-25, 1999.

Habib, M. B. & Ruff, C. B. The effects of locomotion on the structural characteristics of avian limb bones. *Zool. J. Linn. Soc., 153(3)*:601-24, 2008.

Johnsgard, P. A. *The Quails, Partridges, and Francolins of the World*. Oxford, Oxford University Press, 1988.

Kupczik, K.; Dobson, C. A.; Fagan, M. J.; Crompton, R. H.; Oxnard, C. E. & O'Higgins, P. Assessing mechanical function of the zygomatic region in macaques: validation and sensitivity testing of finite element models. *J.Anat., 210(1)*:41-53, 2007.

Lanyon, L. E. & Baggott, D. G. Mechanical function as an influence on the structure and form of bone. *J. Bone Joint Surg. Br., 58-B(4)*:436-43, 1976.

Nordin, M. & Frankel, V. H. *Basic Biomechanics of the Musculoskeletal System*. Baltimore, Lippincott Williams and Wilkins, 2001.

Rayfield, E. J. Finite element analysis and understanding the biomechanics and evolution of living and fossil organisms. *Annu. Rev. Earth Planet. Sci., 35*:541-76, 2007.

Ross, C. F. Finite element analysis in vertebrate biomechanics. *Anat. Rec. A Discov. Mol. Cell. Evol. Biol., 283(2)*:253-8, 2005.

Selker, F. & Carter, D. R. Scaling of long bone fracture strength with animal mass. *J. Biomech., 22(11-12)*:1175-83, 1989.

Zeffer, A.; Johansson, L. C. & Marmebro, A. Functional correlation between habitat use and leg morphology in birds (Aves). *Biol. J. Linn. Soc., 79(3)*:461-84, 2003.

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