Patterns and variations in morphology of glenoid cavity in mammals: Implications for locomotion efficiency

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SUMMARY

The aim of this study was to evaluate and compare the morphology and dimensions of glenoid cavity and examine their relationship with body size and locomotion efficiency. The study was performed on 356 glenoid cavities from 178 mammals, representatives of all major taxa from rodents, sirenians, marsupials, pilosa, cetaceans, carnivores, ungulates, primates and apes. Parameters measured included cranio-caudal and lateral-medial diameters and their ratios; areas of articular surfaces; glenoid cavity index; angles-alpha, -beta and -gamma and length of supraglenoid tubercle and coracoid process. Images were taken using computed tomographic (CT) scanning technology (CT-Aquarium, Toshiba and micro CT- LaTheta, Hotachi, Japan) and measurement values were acquired and processed using Avizo computer software and CanvasTM 11 ACD systems. Statistical analysis was performed using Microsoft Excel 2013. Results obtained showed that mammals exhibit various patterns in the morphology of glenoid cavities that may be associated with adaptation of the glenohumeral joint to robust mobility for locomotion. When the diameters of glenoid cavities were compared between groups of mammals, significant difference was observed in diameters of articular surfaces between rodents and ungulates (1.34±0.32); carnivores and primates (1.39±0.16); primates and rodents and carnivores (1.3±0.12) and between ungulate and carnivores, rodents and primates (1.19±0.18). The mean values of glenoid cavity index in ungulates were found to be lower (0.15±0.13) than those of carnivores (0.22±0.71) and apes (0.26±0.16), indicating that the depth of glenoid cavities of ungulates is shallow compared to those of carnivores and apes. The inclination of the scapula relative to the trunk was found to be tilted lateromedially in apes; mediolaterally in primates (monkeys); craniocaudally in carnivores; vertically in ungulates and cranially in diggers. Significantly, the angles were wider in apes but narrower in ungulates. The length of supraglenoid tubercle was long in ungulates but short in carnivores while the coracoids process was short in ungulates but long in primates and moderately in carnivores and other mammals. The morphological characteristics of the glenoid cavities and the functional interpretation of the parameters in mammals are discussed in detail.

Keywords: Mammalian, Glenoid cavity, Morphology, CT analysis

INTRODUCTION

The scapula bears the glenoid cavity which articulates with the head of the humerus at the shoulder joint. The morphology of the glenoid cavity is highly variable and its rim presents a notch in its proximal and cranial location (MaClatchy et al., 2000;

Provencher et al., 2015). Various shapes including pear-shape, oval or inverted comma of the glenoid cavity occur in humans due to presence of the glenoid notch (Prescher and Klümpen, 1997; Rajput et al., 2012; Dhindsa and Singh, 2014). The anatomical basis and variations of shape and size of glenoid cavity is of fundamental importance in understanding the rotator cuff disease and shoulder dislocation.

The shoulder joint is stabilized by glenoid labrum, the rotator cuff muscles, tendons and ligaments by providing great range of movements of the proximal extremities (Wilk et al., 1997). The glenoid labrum is a ring of triangular shape in section overlying the peripheral circumference of the glenoid cavity with its free rim projecting into the joint (Mulligan and Pontius, 2005). It consists of dense fibrous tissue.

Its base is attached to the margin of the glenoid cavity by fibrocartilage and fibrous bone (Mink et al., 1979). The glenoid labrum is attached to the glenohumeral ligaments and blends cranially with the origin of the long head of the biceps brachii tendon at the supraglenoid tubercle. Its function is to increase congruity and generate suction effect and enhance stability of the shoulder joint (Provencher et al., 2015).

The rotator cuff in primates consists of four muscles: subscapularis, supraspinatus, infraspinatus and teres minor which lie deep to the deltoideus and confer both motion and stability to the shoulder joint (Kuechle et al., 2000; Kato et al., 2012). Supraglenoid tubercle is a small, rough projection cranial to the glenoid cavity close to the base of the coracoid process. It is the origin of the long head of biceps brachii. The coracoid process is a thick curved process originating from the neck of the glenoid cavity (Robert, 1974). The process forms origin of the short head of biceps brachii and coracobrachialis (Greig et al., 1952; Sargon et al., 1996). Long head of biceps brachii holds the head of the humerus in the glenoid cavity, weakly causes flexion of the shoulder joint and abduction of the forelimb while the short head adducts the forelimb.

The coracobrachialis causes flexion of shoulder joint (Provencher et al., 2015). The pectoralis minor which insert on the coracoid process also causes abduction of the forelimb. Both, the supraglenoid tubercle and coracoids process serve to stabilize the shoulder joint.

Variations in the morphology of glenoid cavity have resulted into varying mobility of the shoulder shoulder joint and hence a wide range of locomotor functions from terrestrial pronograde quadrupedalism to highly arboreal suspensory behaviours such as brachiating, hanging and vertical climbing (Young, 2006). Forelimb functions are therefore considered to play a major role in shoulder joint mobility and pattern intraspecific variations in glenoid cavity among mammals. The purpose of this study was therefore to evaluate and compare the morphology and dimensions of glenoid cavity and examine their relationship with body size and locomotion efficiency and establish possible morphofunctional correlations related to mammalian taxa and species.

MATERIALS AND METHODS

Source of specimens

A total of 356 scapulae from 178 adult mammals were obtained from various areas in Japan including the National Science Museum, Tsukuba, Tokyo; Primate Research Institute, Kyoto University; Ueno Zoological Gardens, Tokyo; Tama Zoological Park, Tokyo; Saitama Children's Zoological garden, Saitama; Himeji Central Park, Hyogo; Asa Zoological garden, Hiroshima; Akiyoshidai Natural Animal Park Safari Land, Yamaguchi; Tokuyama Zoological garden, Yamaguchi; Tokiwa Zoological garden, Yamaguchi; Wan Park Kochi Animal Land, Kochi; Tsushima Wildlife Conservation Center, Nagasaki; Yambaru Wildlife Conservation Center, Okinawa; Wild animals Unit, Yamaguchi and Laboratory animal unit, Yamaguchi University.

Measurements of glenoid parameters, data acquisition and processing

All computed tomographic (CT) scanned images of glenoid cavities were processed using computer software. Measurement values of glenoid cavities were acquired and processed using Avizo version 6.1.1, Maxnet, Japan.

Reference points of glenoid angles

A-angle alpha was measured as the angle between a line drawn along the scapular body through supraglenoid tubercle to the level of lateral margin and a line connecting the cranial and caudal scapular body through supraglenoid tubercle to the level of medial margin; B-angle beta was measured as the angle between a line drawn along the scapular body through supraglenoid tubercle to the level of lateral margin and a line drawn along the coracoid process and C-angle gamma was measured as the angle between a line segment drawn laterally from the center of glenohumeral contact and a line drawn along cranial margin of the acromion process. Variation in the dimension of the angles influences the scapular inclination relative to the trunk.

RESULTS

Measured parameters

Parameters measured included 1, cranio-caudal diameter-; 2, lateral-medial diameter; 3, length of supraglenoid tubercle; 4, angle-alpha, α; 5, length of coracoid process; 6, angle-beta, β; 7, length between center of glenoid and acromion and 8, angle-gamma, γ and glenoid index (Figure 1). Data on articular surface areas of glenoids were generated using CanvasTM 11 ACD systems, America. Statistical analysis on variance between measurements was performed using Microsoft Excel 2013.

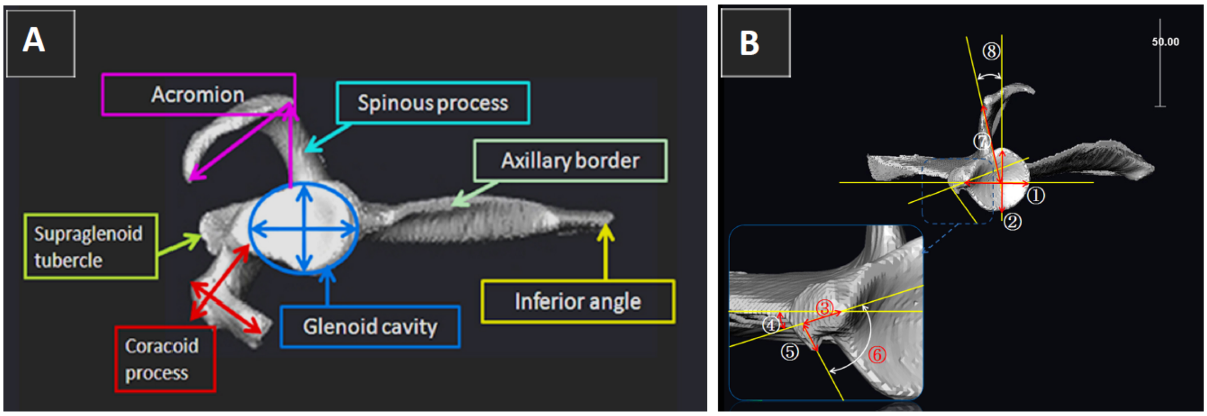

Figure 1. Ventral view of primate scapula showing various measurements. **(A)** Outline scapular features characterized by various anatomical structures as seen from glenoid cavity **(B)** Numbers representing points used to take glenoid measurements: 1, cranio-caudal diameter; 2, lateral-medial diameter; 3, length of supraglenoid tubercle (infra-glenoid tubercle); 4, angle-alpha, α; 5, length of coracoid process; 6, angle-beta, β; 7, length between center of glenoid cavity and acromion; 8, angle-gamma, γ. Scale: 50.0 mm

Morphological patterns of glenoid cavities

Mammals exhibit various patterns in the morphology of the glenoid cavities; being spherical shaped in carnivores; circular shaped without any distinct notch in ungulate; oval shaped in primates and apes; circular shaped with long acromion process in shrew, rat and marsupials; oval shaped in mole, ellipsoidal in porpoise and irregular in echidna and platypus (Figure 2)

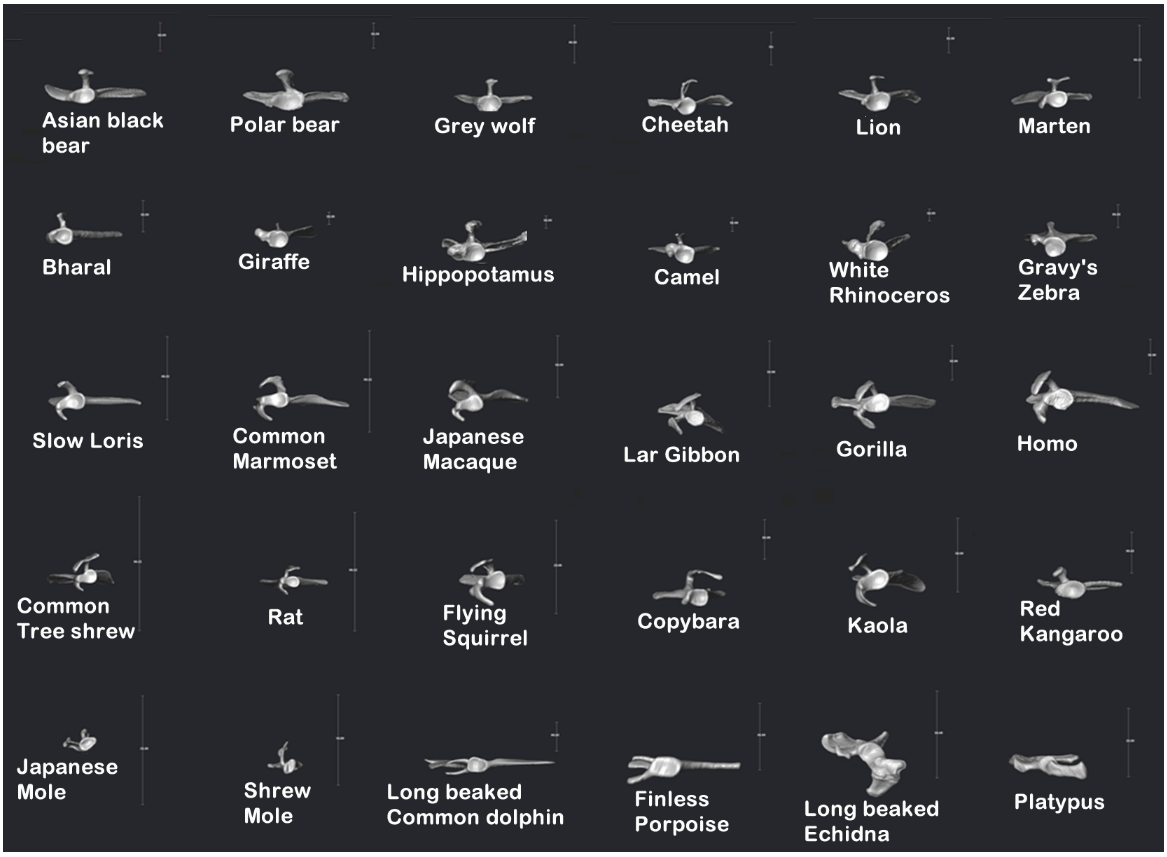

Figure 2. Shapes of glenoid cavities of mammalian species studied. Note the spherical shape glenoid cavity of carnivores in the first row; circular shape without any distinct notch in ungulate in the second row; oval shape in primates and apes in the third row; circular shape and long acromion process in shrew, rat and marsupials in the fourth row; and in firth row the oval shaped in mole, ellipsoidal in porpoise and irregular in echidna and platypus. Scale: 50.0 mm

Diameter of the articular surface of the glenoid cavity.

Despite the variations in the shape of glenoid cavity, the diameter of articular surface in cranio-caudal (R2= 0.884) and medio-lateral (R2=0.9) orientation correlated well with the body weight (Figure 3).

When the diameters of glenoid cavities were compared between groups of mammals, significant difference ($P \leq 0.05$) was observed between rodents and ungulates (1.34±0.32, mean value difference); carnivores and primates (1.39±0.16); primates and rodents and carnivores (1.3±0.12) and between ungulate and carnivores, rodents and primates (1.19±0.18) [Figure 4]

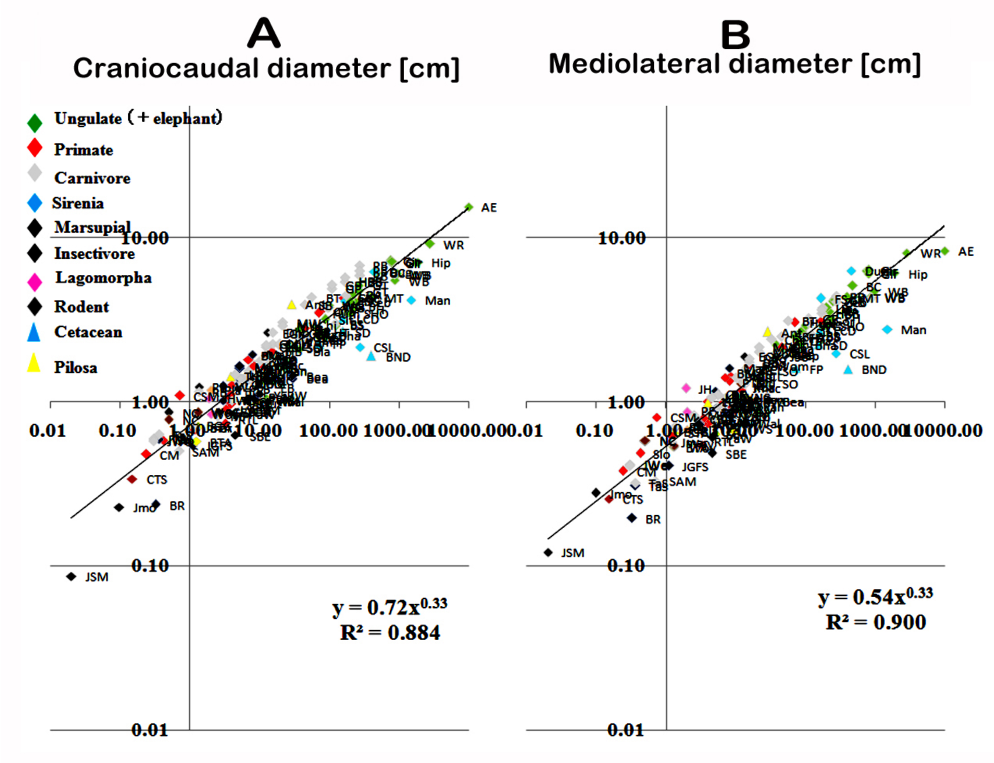

Figure 3. Scatter plot of the diameter of glenoid cavities. The diameter of articular surface of the glenoid cavity **(A)** cranio-caudal (R^2= 0.884) and **(B)** medio-lateral (R^2=0.9) correlates well with the body weight or size of animal.

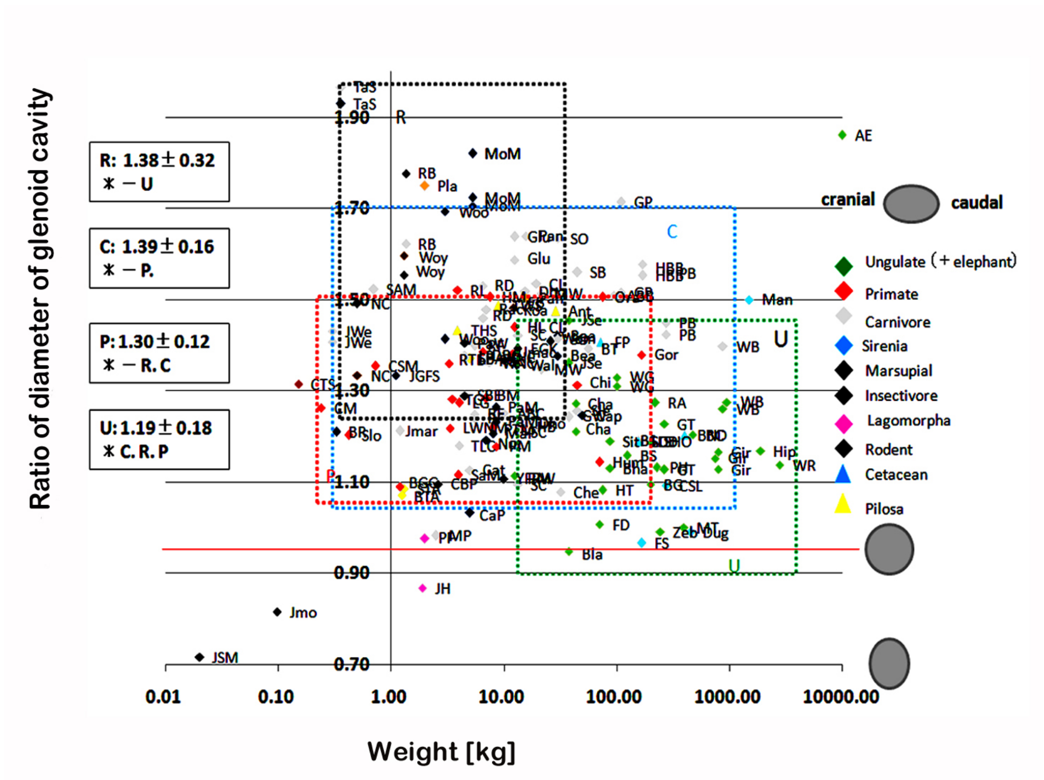

Figure 4. Scatter plot showing the ratio of diameters of glenoid cavities. There are statistically significant differences in the diameter of glenoid cavities among mammals. Rodents differed with ungulates ($P \leq 0.05$) in the mean of the two groups (1.38±0.32); carnivores with primates (1.39±0.16); primates with rodents and carnivores (1.3±0.12) and ungulates with carnivores, rodents and primates (1.19±0.18).

The ratio of area of articular surface of the glenoid cavity to body weight of animal

The ratio of the topographical area of the articular surface the glenoid cavities to body weight of an animal assessed by CanvasTM 11 ACD systems was found to be smallest in rodents such as the moles, moderately large in carnivores and primates and largest in ungulates (Figure 5).

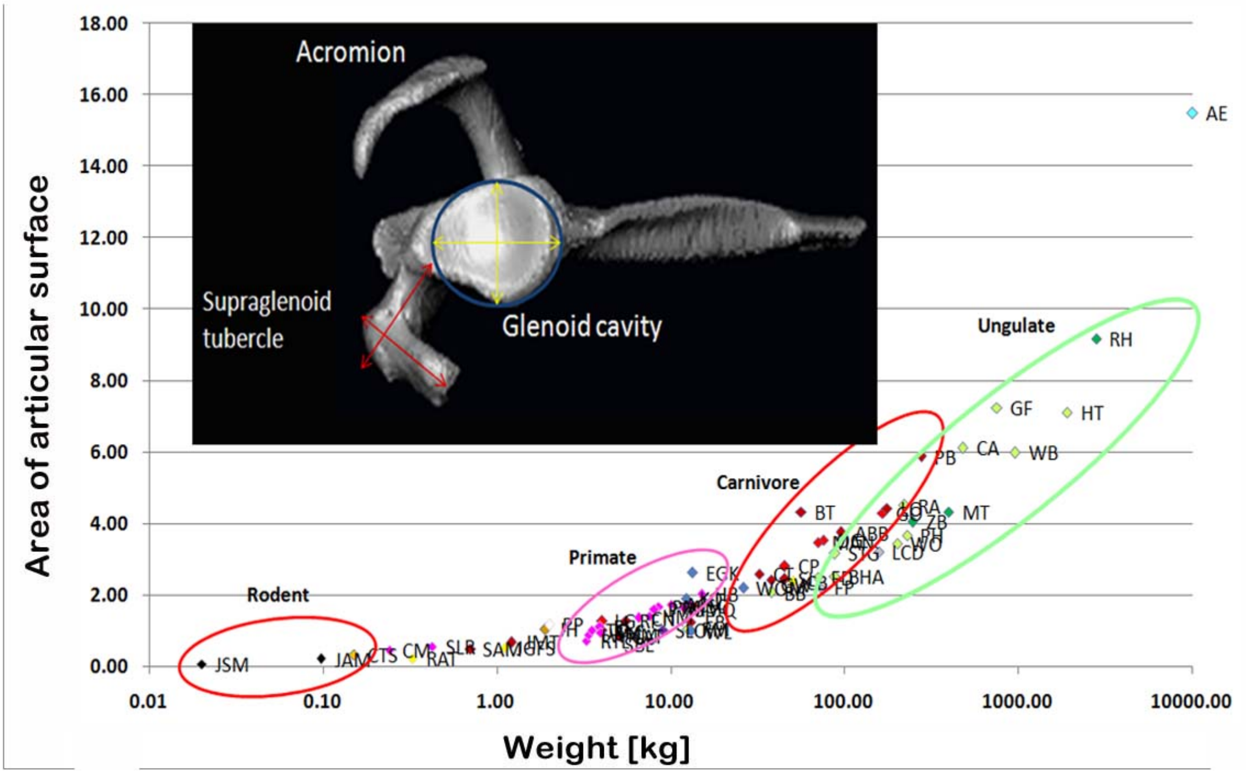

Figure 5. Scatter plot of view of primate scapula showing area of articular surface of glenoid cavity. Area of articular surface is largest in ungulates; moderately in carnivores; small in primates and much smaller in rodents, indicating that the larger the animal the larger the area of articular surface of the glenoid cavity.

The glenoid cavity index (GCI)

The glenoid cavity index is the ratio of the diameter before and after articular surface to the maximum length of the scapula assessed by CanvasTM 11 ACD systems. The mean values of GCI in ungulates was found to be lower (0.15±0.13) than those of carnivores (0.22±0.71) but it was highest in apes (0.26±0.16).

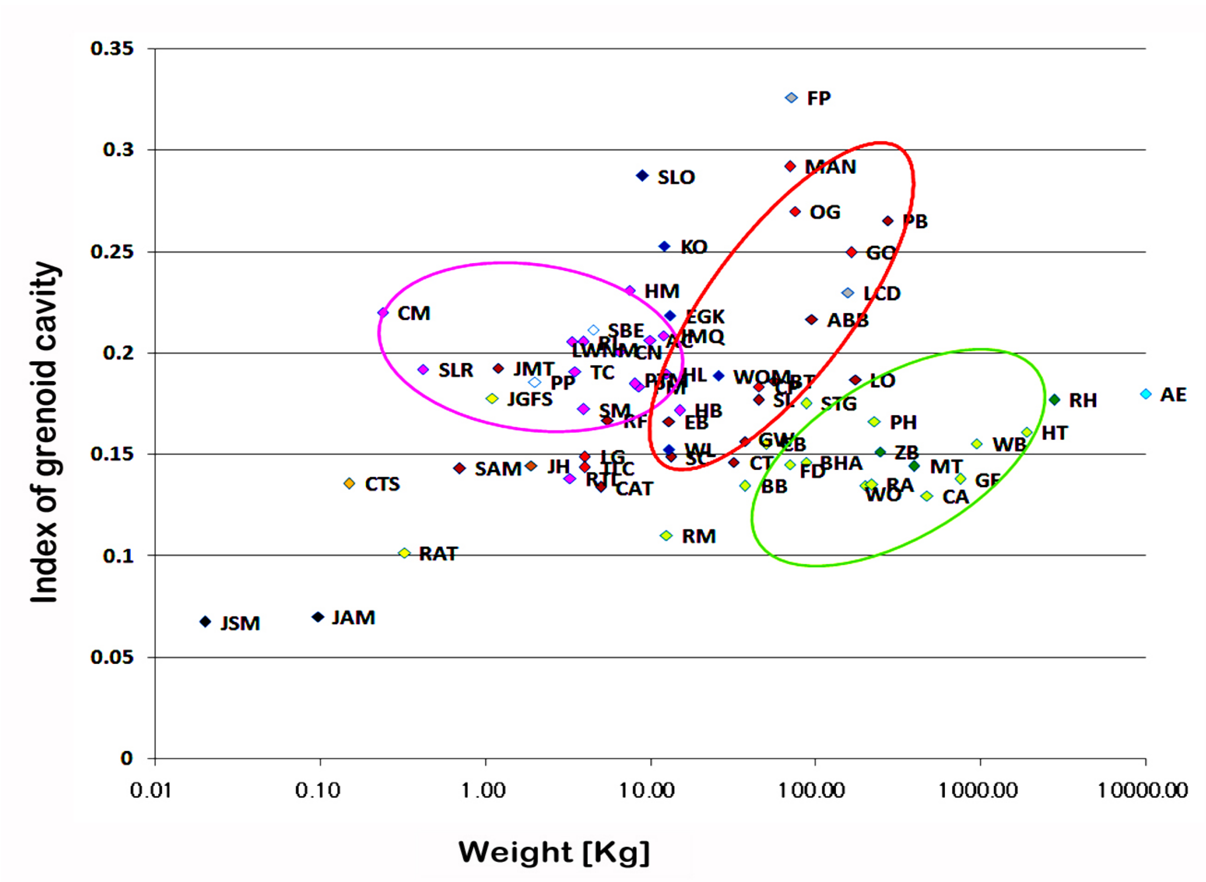

Figure 6. Scatter plot showing glenoid cavity index. The index is highest in apes, moderate in carnivores and lower in ungulates indicating that the glenoid cavity of ungulates is shallow compared to apes and carnivores.

Characteristics of glenoid angles: angle-alpha (α); angle-beta (β); and angle-gamma (γ)

Analysis was done to determine the relationship of the position of glenoid cavity relative to the medial border of the scapula. It was noted that the glenoid cavity is tilted lateromedially in apes; mediolaterally in primates; craniocaudally in carnivores; vertically in ungulates and cranially in diggers. Generally, the inclination angles were wider in apes and narrower in ungulates (Figure 7).

Length of supraglenoid tubercle and coracoid process

The length of supraglenoid tubercle was long in ungulates, moderate in primates and other animals but it was short in carnivores. The coracoid process was short in ungulates but long in primates and moderate in carnivores and other mammals (Figure 8).

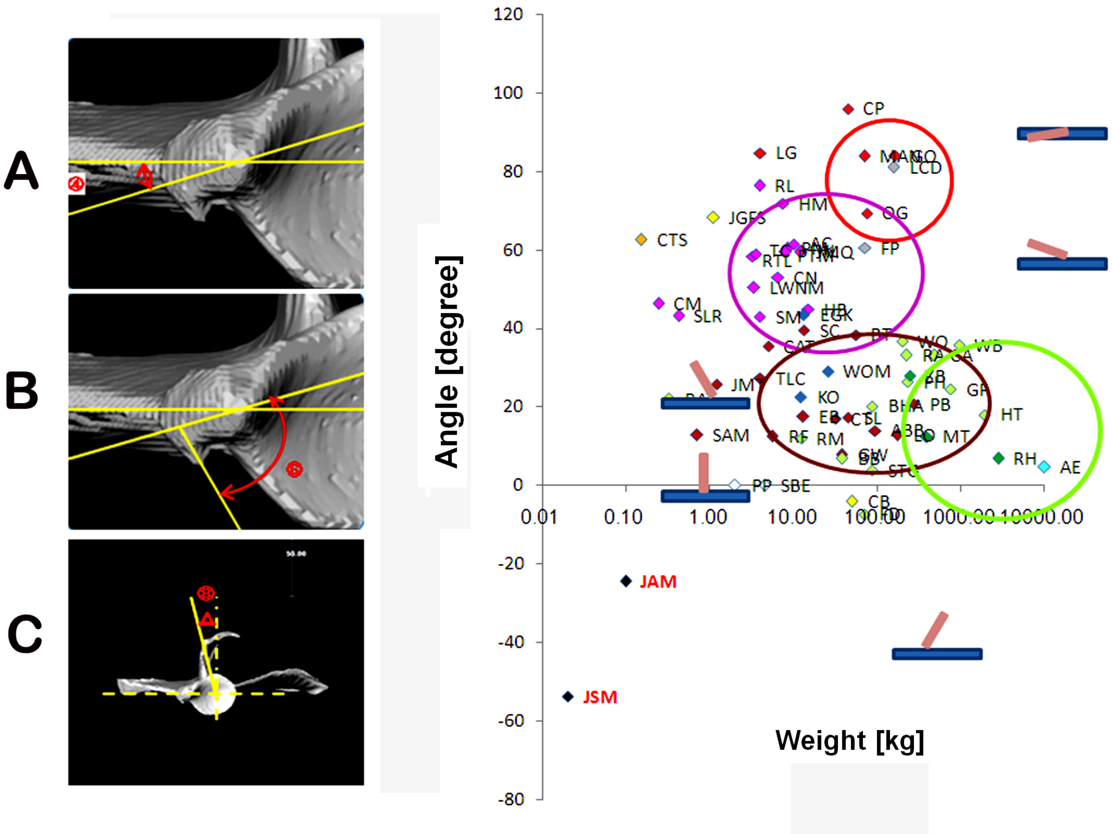

Figure 7. Plates and scatter plot of the angles of glenoid cavity. Plates show angles of the glenoid cavity **(A)** Angle-alpha, α; **(B)** Angle-beta, β; and **(C)** Angle-gamma, γ. Blue bars indicate relationship between position of glenoid cavity relative to the medial border of the scapula. In apes (red circle) glenoid cavity is tilted latero-medially; in primates (orchid) it is mediolaterally; in carnivores (maroon) it is craniocaudally; in ungulates (green) it is vertically and in diggers (JAM, JSM) it is cranially. Generally, the inclination angles are wider in apes (red circle) and narrower in ungulates (green circle).

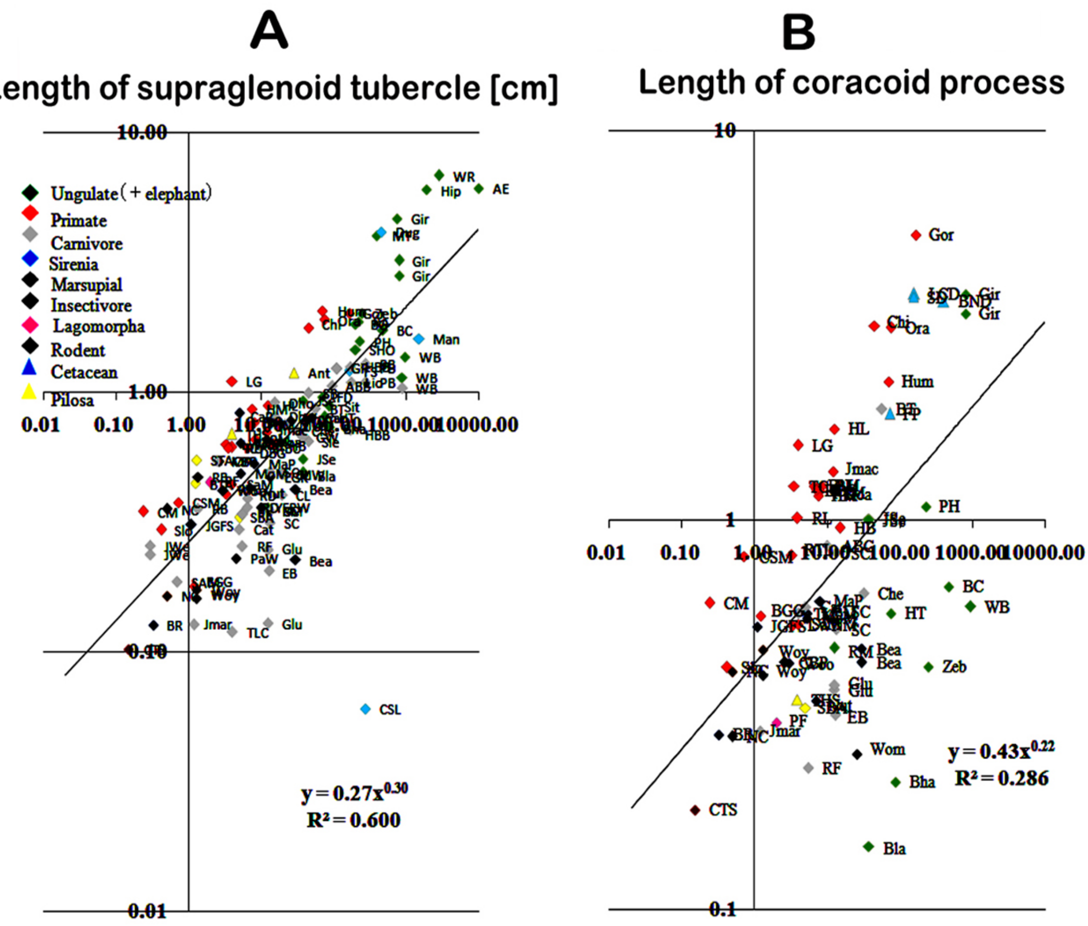

Figure 8. Scatter plot showing length of supraglenoid tubercle and coracoid process. **(A)** The length of supraglenoid tubercle is long in ungulates but short carnivores while intermediate in primates and other mammals. **(B)** The length of coracoid process is long in primates but short ungulates and intermediate in carnivores and other mammals.

DISCUSSION

Comparative studies on the morphology of the glenoid cavity in mammalian have been a focal point in understanding the rotator cuff disease and shoulder dislocation (Roberts, 1974).

Features of glenoid including glenoid cavity, glenoid lubrum, glenoid capsule, supraglenoid tubercle and coracoid process, have been associated with degree of mobility and stability of the shoulder joint during movement (Inouye and Shea, 1997).

In this study, 356 glenoid cavities from 178 mammals were evaluated and analyzed so as to obtain data on the comparative morphology of glenoid cavities among mammals. The study has deduced the relationship of the body size and locomotion with parameters of glenoid cavity such as cranio-caudal and lateral-medial diameters and their ratios; areas of articular surfaces; angles-alpha, -beta and -gamma and length of supraglenoid tubercle and coracoid process so as to establish possible morphofunctional correlations related to mammal taxa and species.

In this study, the shape of glenoid cavity was found to vary among mammals being spherical in carnivores; circular without any distinct notch in ungulate; oval in primates and apes; circular with long acromion process in shrew, rat and marsupials; oval in moles, ellipsoidal in porpoises and irregular in echidna and platypus. Variation in the shape of glenoid cavity may reflect the presence of differences in mobility of the shoulder joint and speed of locomotion amongst animals or involvement in training and exercise. Increased capabilities for running and jumping on rough grounds in ungulates is made possible by the shallow glenoid cavity and help to increase mobility of the shoulder joint and avoid frequent dislocation.

Furthermore, there were also statistically significant differences in the diameter of glenoid cavity among mammals. Rodents differed with ungulates (1.38±0.32; mean diameter); carnivores with primates (1.39±0.16); primates with rodents and carnivores (1.3±0.12) and ungulates with carnivores, rodents and primates (1.19±0.18).

The cause for the statistical grouping of the animals signifies presence of a close relationship between habitat and type of locomotion. Indeed, data on the ratio of diameters showed that the spatial orientation of the glenoid cavity relative to the trunk was medio-lateral in ungulates but it was cranio-caudal in carnivores. In apes and primates, the pear shaped glenoid cavity with the presence of craniodosaral notch appears to favour mobile shoulder joint (MaClatchy et al., 2000) which is an adaptation for rapid limb motion and suspensory actions (Larson, 1993; Taylor, 1997).

The length of supraglenoid tubercle was also long in ungulate to stabilize the shoulder joint during limping and jumping movements. The coracoid process was long in apes and primates to stabilize the humeral head within the glenoid fossa during suspensory actions.

In conclusion, results of this study have demonstrated that there are variations in the shape and depth of glenoid cavity among mammals and this reflects the existence of differences in mobility of the shoulder joint which is enhanced by training and exercise.

However, it is worth noting that collecting more data for some taxa with variability in locomotor modes may give additional information on the association of variations in the shape of glenoid cavity with habitat or ecology and type of locomotion.

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