Study of Shape of Proximal End of Humerus in Thais: Using Geometric Morphometrics

ศึกษารูปร่างบริเวณปลายบนของกระดูกต้นแขนในคนไทยโดยวิธีจีโอเมทริก มอร์โฟเมทริกส์

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ABSTRACT

The present study aimed to compare the shape and size of articular head, greater and lesser tubercles of the proximal end of humerus among genders, sides and age groups in Thais. 160 humeri were photographed on anterior, posterior, lateral, medial and superior aspects then analyzed shape and size of all aspects using by geometric morphometric technique. The result showed significant shape and size difference between genders and age groups but sides comparison revealed no significant difference. The knowledge of shape of proximal humerus can be benefit to orthopedic surgeon for humeral head prosthesis or tendon repair and useful in forensics for identifying individual.

บทคัดย่อ

การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อเปรียบเทียบรูปร่างและขนาดของส่วนหัวและปุ่มกระดูกบริเวณปลายบนของกระดูกต้นแขนระหว่างข้าง, เพศ และกลุ่มอายุในคนไทย โดยกระดูกต้นแขน จำนวนทั้งหมด160 ชิ้นถูกนำมาถ่ายรูปทั้งห้าด้านคือ ด้านหน้า, ด้านหลัง, ด้านนอก, ด้านใน และด้านบน จากนั้นทำการศึกษารูปร่างและขนาดด้วยวิธีจีโอเมทริก มอร์โฟเมทริกส์ โดยผลที่ได้พบว่ารูปร่างและขนาดมีความแตกต่างกันอย่างมีนัยสำคัญทางสถิติระหว่างเพศและกลุ่มอายุ โดยระหว่างข้างซ้ายและขวาไม่มีความแตกต่างของรูปร่างและขนาดอย่างมีนัยสำคัญทางสถิติ รูปร่างของส่วนต่างๆในบริเวณปลายบนของกระดูกต้นแขนที่ได้จากการศึกษาในครั้งนี้จะมีประโยชน์ต่อการผ่าตัด เช่น การใส่อุปกรณ์เทียมในส่วนหัวของกระดูกต้นแขน การซ่อมเอ็นกล้ามเนื้อที่มีจุดเกาะบริเวณปลายบนของกระดูกต้นแขน และความต่างของรูปร่างและขนาดบริเวณปลายบนของกระดูกต้นแขนยังสามารถใช้ในการระบุตัวตนทางนิติวิทยาศาสตร์

Keywords: Proximal humerus, Geometric Morphometrics

คำสำคัญ: กระดูกต้นแขนส่วนต้น จีโอเมทริก มอร์โฟเมทริกส์

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Introduction

Shoulder problem is the third most musculoskeletal pain in England (Urwin et al., 1998) and another study showed an incidence of shoulder problem in Netherlands was 29.3 per 1000 person-years during 1998 to 2007 (Greving et al., 2012). In Thailand, it was revealed that prevalence of shoulder pain 16% in office workers (Janwantanakul et al., 2008) and recent study showed incidence of shoulder pain was 30.2% in the 2-months follow-up of university staff (Sunisa and Maytinee, 2015). Shoulder problem is multifactorial causes, it can be occupational work related due to repetitive function (Leclerc et al., 2004) or work related posture (Pope et al., 1997), degenerative change in aging, and gender specific bony morphology (Yamamoto et al., 2010; Balke et al., 2013). As form and function concept, it has been suspected that different morphology of related bony structure can lead to musculoskeletal problem, causing joint instability and pain. However, different shape is sometime appropriated for different functions. Research in shoulder joint problem is mostly examined in the scapula while the humeral is less mentioned particularly involving its morphology.

The proximal part of humerus is important and plays a crucial role in shoulder movement because it is composed of hemispheric head to form shoulder joint and bony prominences for muscle attachment which strongly support the joint. Humeral head has a distinctive shape as hemisphere and forms part of shoulder joint, however the humeral head was revealed slightly different in shape in individual (Saha et al., 1971). Previous studies reported the vertical diameter of humeral head in male was larger than female (Sikka et al., 2016; Lokanadham et al., 2013). Another works measured various aspects of humeral head and revealed no significant difference between sides (Ashutosha et al., 2017; Akman et al., 2006). The tubercles on the proximal end of humerus were attached sites of rotator cuff tendons that play a crucial role in stabilizer of the glenohumeral joint. For the reason of that, it frequently encountered problem of tendinitis or tendinous tear around this area. A study done by Yamamoto et al. (2010) reported the prevalence of the rotator cuff tear in Japan was 20.7% of 1,366 shoulders and caused of rotator cuff tear was mostly related to trauma, dominant arm and age. Recent studies on rotator cuff footprint and measured its dimension shined up to repair rotator cuff tear and placing the appropriate suture (Curtis et al., 2006; Mochizuki et al., 2008; Vosloo et al., 2017).

A morphometric method is the techniques used to determine the morphology of any structures such as bone. It is a quantitative shape configuration, relies on measurement of distance between two bony landmarks as a linear measurement (Zelditch et al., 2004) but not well fit to more complicated structure and always has size effect in the shape information, recent method using Cartesian coordinate system to examine shape which called the geometric morphometrics. It provides more precise and accurate shape information (Gomez et al., 2012). There are two methods, one is defined the landmark on homologous point of the bone called “landmark base”, second is defined the contour around that object such as part of the bone called “outline base”. The outline base method is frequently uses for specimen which not have clear prominent landmark. The data will later analyze statistically using computer program (Mitteroecker et al., 2009).

Previous studies of human humerus morphology using the linear measurement did not actually describe the shape (Akman et al., 2006; Ali et al., 2016) since there was also size present while the geometric morphometric

method has been accepted that to give the real shape information and widely used. Recent studies on primate showed the shape of humeral head difference using landmark base of 3D geometric morphometrics, *Hylobates* appeared the greater circumduction of the articular surface that enhance for large range of the glenohumeral joint in anteroposterior direction and revealed the alignment of insertion site of the rotator cuff on the humeral tubercles associated with the divergent forces in diferrence of locomotor patterns (Arias et al., 2015) and the same technique, the whole shape of humerus showed more straight shaft in nonquadrupedal hominoids than other taxa, following axial compressive load in quadrupedal locomotion that lead to humeral shape bending (Holliday et al., 2013). Other study analyzed the cortical bone thickness at muscle or tendon attachment site of whole humerus in primates revealed the high cortical bone thickness in the brachiators indicating that suspensory primates produce passive tension more than quadrupedal primates (Kikuchi et al., 2012). The human humerus is probably difference in each individual that difference due to daily activities, hormones or dominant arm. Although, several anatomical textbooks have mentioned about the general shape of humerus but with the geometric morphometric technique, however it's still scanty in human. The knowledge of shape of proximal humerus can be benefit orthopedic surgeon for humeral head prosthesis or tendon repair and useful in forensics for identifying individual.

Objective of the study

The aim of present study was to compare morphology of proximal end of humerus especially the articular segment and the rotator cuff footprint on the greater and lesser tubercles in anterior, posterior, lateral, medial and top views using geometric morphometric technique between sides, genders and age groups.

Materials and methods

Specimens

This study has been approved by the Siriraj Institutional Review Board (SIRB) (059/2561). All specimens were obtained from Department of Anatomy, Faculty of Medicine Siriraj Hospital, Mahidol University. All cadavers with known gender, age, and without proximal end of humerus fracture or pathological changes and complete both sides were collected. The demographic data was recorded as ID code, side, gender and age. Eighty paired of humeri were assigned for comparison study in3 groups; left and right for side group, male and female for gender group and below and above or equal to 60 years for age group.

Specimen was clean by removing all of skin, muscles, soft tissue and ligament surrounding glenohumeral joint. The humeral bones were immersed in 35% potassium hydroxide (KOH) about twenty-four hours for crumbling articular cartilage and remaining soft tissue around the humeral head such as rotator cuff tendon and then they were cleaned and dried. After that proximal ends of humerus were photograph for further measurement. During dissection, the rotator cuff tendon was investigated and its footprint was observed.

Photographs of proximal humerus

A total of 160 well-preserve humeri, each humerus placed on bone holder stand with rotational disk. The camera connected with the computer notebook for using the gridline to monitor bone position. The bone was set in

anatomical position and fixed onto a bone holder-stand which mounted on the rotatory disk. This study was planned to investigate several aspects of proximal humerus, the consistency of image taking is crucial to eliminate bias. All of the bones were set at distance 28 centimeters from the lens of camera to the bone. All of specimens were photographed starting from anterior aspect that revealed the humeral head and lesser tubercle, the humeral position was adjusted to keep the lateral edge of the lesser tubercle touched the middle gridline in the camera screen, then the rotational disk was turned 180 degrees to get posterior view and adjusting the bone until the lateral edge of the greater tubercle touching the defined line. Later, the rotational disk was turned further 90 degrees to expose lateral aspect of humerus and reveal the whole thickness of the lesser tubercle and then the bone was adjusted until the anterior edge of the greater tubercle and lateral lip of intertubercular groove touches the middle gridline. Finally, the rotational disk was turned 180 degrees to disclose medial view and adjusting the bone until the one side of edge of articular head touching the defined line. On the top view, the bone was adjusted until the edge of the humeral head touched the defined line.

Geometric morphometric analysis

Geometric morphometric analysis was done by CLIC99 (Collection of Landmark for identification and Characterization) program which was developed by Dr. Jean-Pierre Dujardin. The program has variety module and different procedure for analyzing shape and size. Initially, all photos were filed separately left and right for side groups, male and female for gender groups and below and above or equal to 60 years for age groups. A comparison study on shape and size of articular head and tubercles of proximal end was taken. The present study used outline base by dawning contour around the articular head, rotator cuff footprints on greater and lesser tubercles (Figure 1). Although the proximal end of humerus has some homologous landmark as the tubercle but it is wide prominence that difficult to make decision for plotting precisely and the result of outline base is the mean shape that reveals the output virtually, thus to use the outline technique is reasonable. A COO module was used for importing the images and plotting the outline of proximal end of humerus, the shape coordination data was processing by the program. The images of the other side was flip to reflect the corresponding outline, this was done before plotting. The digitized outline and centroid were generated by the program.

The graphical output was created as a mean shape of two groups by Generalized Procrustes Analysis (GPA) involving three steps: firstly, all digitize contour is translated to share the same centroid; secondly, digitized contour is rescaled to be in the same scale by adjusting the range of the distant radii from the centroid; thirdly, the digitize outline contour is rotated around its centroid until the distances between points of each configuration were minimal (Figure 2). Elliptic Fourier Analysis (EFA) was applied for computing shape coordination and size. After that, PAD module was used for analyzing statistically by Principal components analysis (PCA) to reduce the number of variables and remove correlations between initial variables then using the Discriminant analysis to classify or separate between groups. Finally, the VAR module was applied to analyze perimeter for computing size difference between groups. The significance level set at $p\text{-value} < 0.05$.

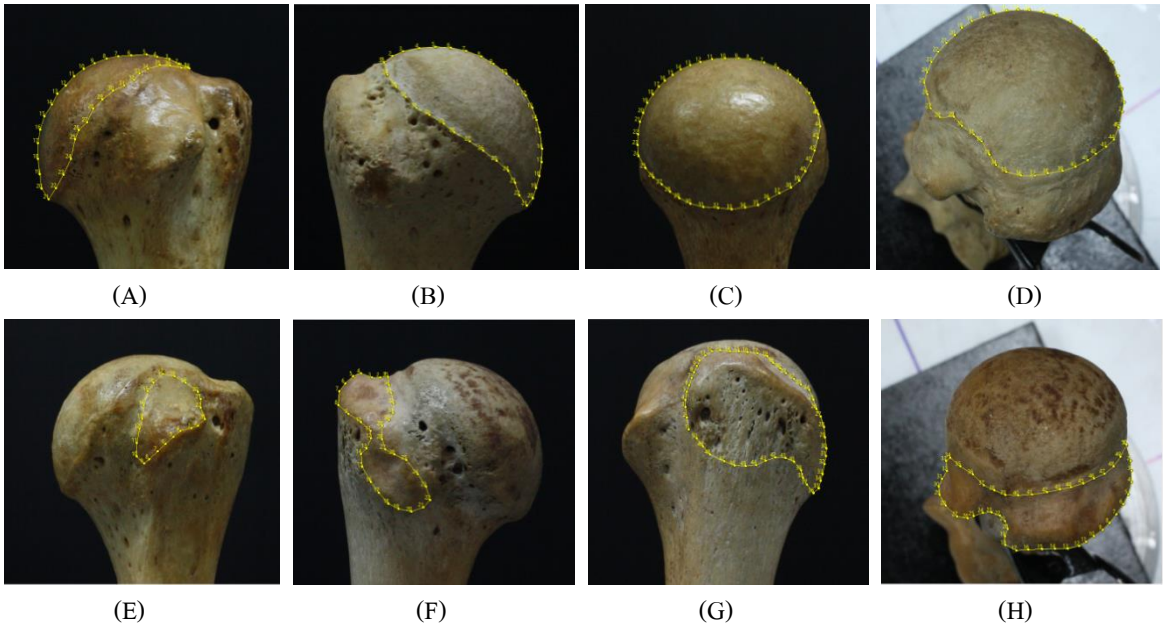

Figure 1 The outline of study areas: articular head on anterior (A), posterior (B), medial(C) and superior aspects (D), the contour of subscapularis footprint on lesser tubercle in anterior aspect (E), the contour of rotator cuff footprint on greater tubercle in posterior aspects (F) and lateral aspect of greater tubercle (G), the outline contour around greater and lesser tubercle on superior aspect (H).

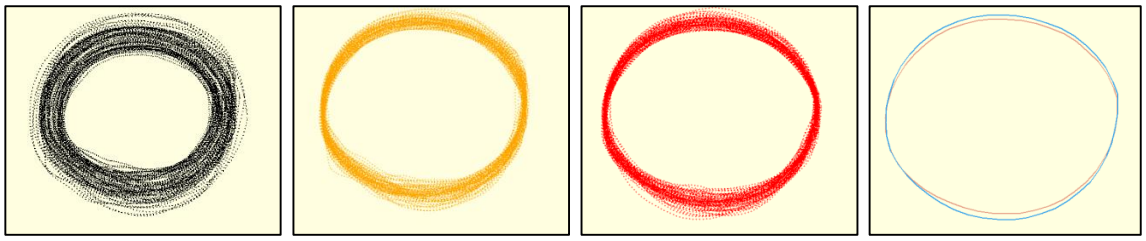

Figure 2 The FOG module generated graphical output of medial aspect of articular head using GPA by translation (A), rescaling (B), and rotation (C) of the shape. The mean shapes in each group (D) were compared for shape difference by multivariate analysis

Results

Anterior and posterior aspect of the articular head gives hemisphere shape (Figure 3-4) and medial aspect reveals only round shape of articular head (Figure 5) while superior aspect of the articular head looks rather round (Figure 6). The comparison of the mean shape of articular head of all aspects showed significant difference between genders and age groups (Table1, Figure 3-6B, C) but between sides not significant difference (Table1, Figure 4-6A), except in anterior aspect that showed difference between sides (Table1, Figure 3A). Size of articular head showed significant larger in male at all aspects (Table1, Figure 3-6B), for superior aspect of articular head displayed significant larger area in elderly group (Table1, Figure 6C).

Subscapularis footprint on lesser tubercle is notable on anterior aspect of humeral head showing as triangular shape (Figure 7). The comparative result exposed significant shape difference only gender comparison (Table1, Figure 7B) and revealed significant larger in male and elderly group (Table1, Figure 7).

Rotator cuff footprint on greater tubercle on posterior aspect of humeral head resembles peanut shape (Figure 8). The result of comparison showed significant shape and size difference between genders and age groups (Table1, Figure 8B, C). Greater tubercle on lateral aspect looks like a large comma shape (Figure 9). The comparison of the mean shape showed significant difference only between age groups (Table1, Figure 9C) and significant larger in male (Table1, Figure 9B).

Tubercles or non-articular area on superior aspect looks like dragger which the lesser tubercle represent the handle of the dragger (Figure 10). The comparative result indicated significant difference of shape between gender and age groups (Table1, Figure 10B, C) and showed significant larger in male (Table1, Figure 10B).

Table 1 The comparison of proximal humerus between sides, genders and age groups

Parameters	Aspects	Shape			Size		
		Sides	Genders	Age groups	Sides	Genders	Age groups
Articular head	Anterior	0.037*	0.009*	0.000*	0.386	0.000**	0.352
	Posterior	0.421	0.000*	0.000*	0.888	0.000**	0.603
	Medial	0.891	0.013*	0.033*	0.347	0.000**	0.456
	Superior	0.613	0.000*	0.000*	0.333	0.000**	0.000***
Lesser tubercle	Anterior	0.234	0.007*	0.393	0.282	0.000**	0.000***
Greater tubercle	Posterior	0.149	0.006*	0.006*	0.936	0.000**	0.013***
	Lateral	0.497	0.203	0.000*	0.936	0.000**	0.195
Tubercles	Superior	0.891	0.013*	0.033*	0.347	0.000**	0.456

*Note: *significant shape difference (p-value < 0.05), **significant size difference male larger than female (p-value < 0.05), ***significant size difference elderly larger than young (p-value < 0.05)*

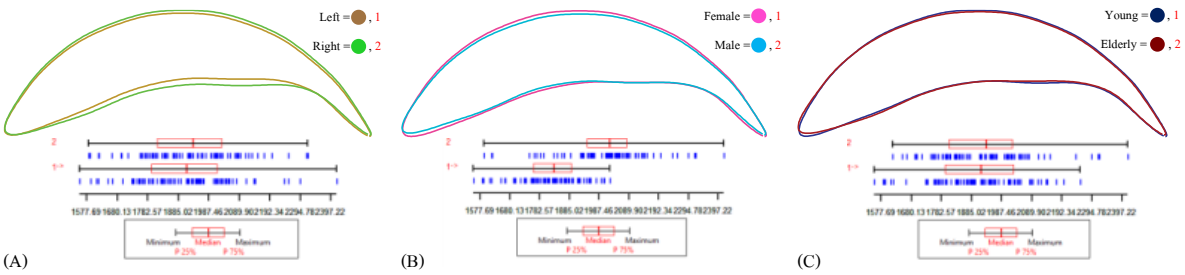

Figure 3 The comparisons of mean shape and box scale of size of articular head on anterior aspect between sides (A), genders (B) and age groups(C)

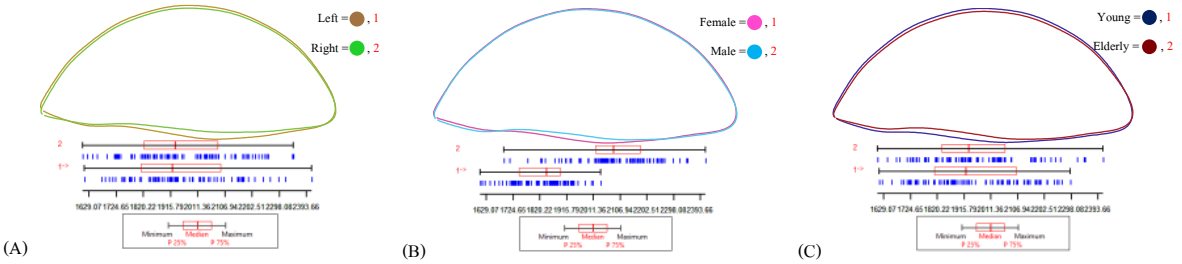

Figure 4 The comparisons of mean shape and box scale of size of articular head on posterior aspect between sides (A), genders (B) and age groups(C)

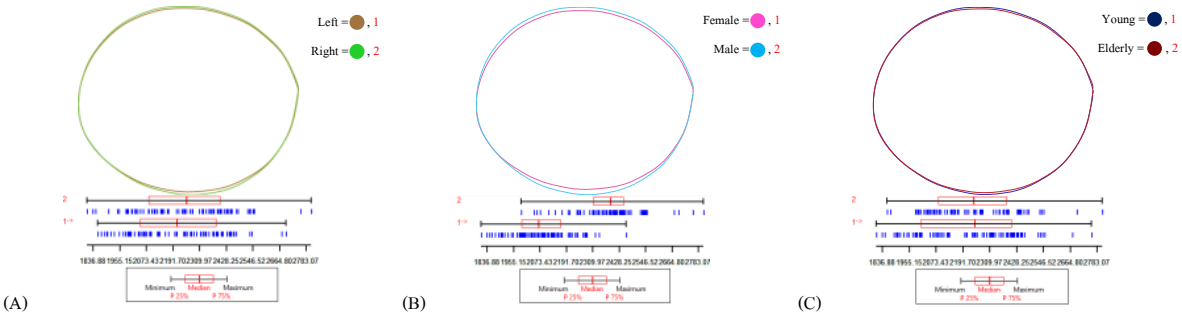

Figure 5 The comparisons of mean shape and box scale of size of articular head on medial aspect between sides (A), genders (B) and age groups(C)

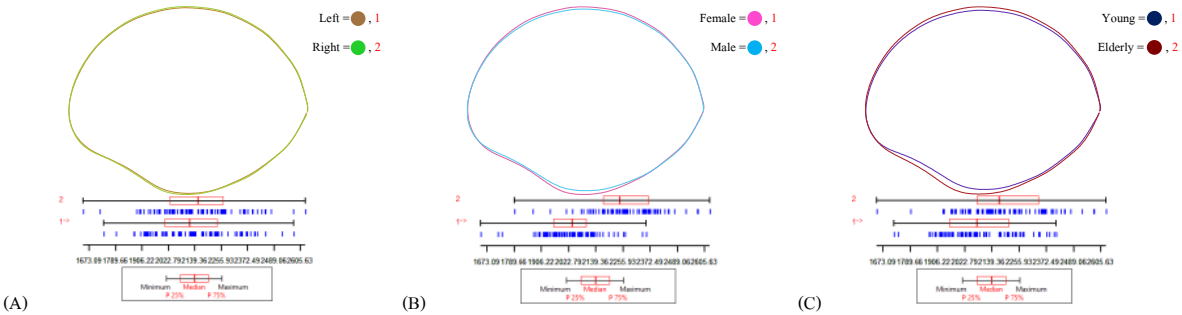

Figure 6 The comparisons of mean shape and box scale of size of articular head on superior aspect between sides (A), genders (B) and age groups(C)

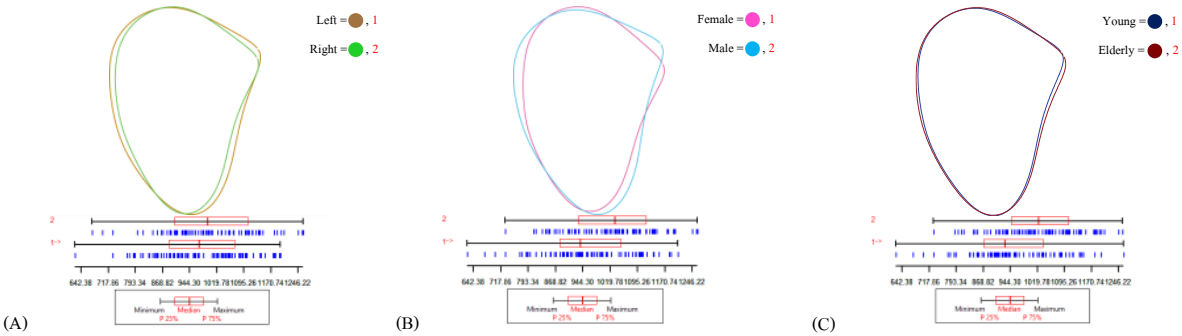

Figure 7 The comparisons of mean shape and box scale of size of the subscapularis footprint on lesser tubercle in anterior aspect between sides (A), genders (B) and age groups(C)

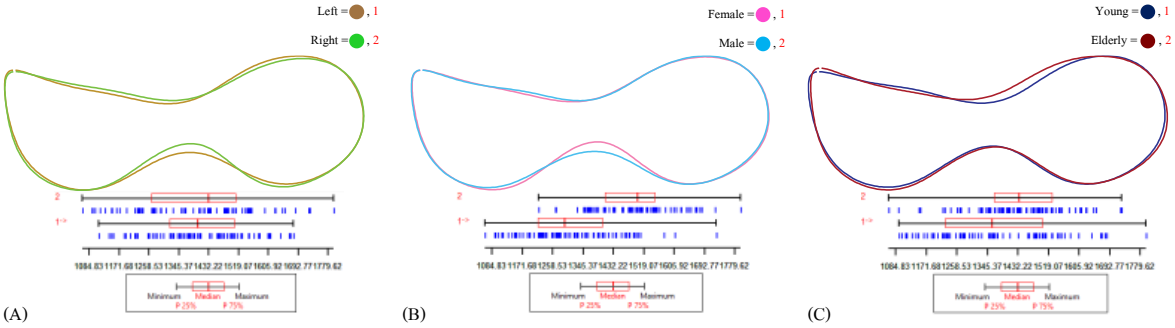

Figure 8 The comparisons of the mean shape and box scale of size of the three tendons of rotator cuff footprint on greater tubercle in posterior aspects between sides (A), genders (B) and age groups(C)

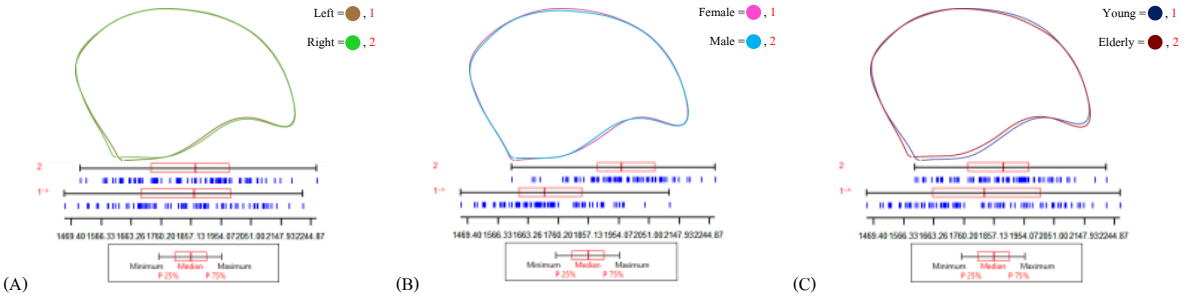

Figure 9 The comparisons of the mean shape and box scale of size of lateral aspect of greater tubercle between sides (A), genders (B) and age groups (C)

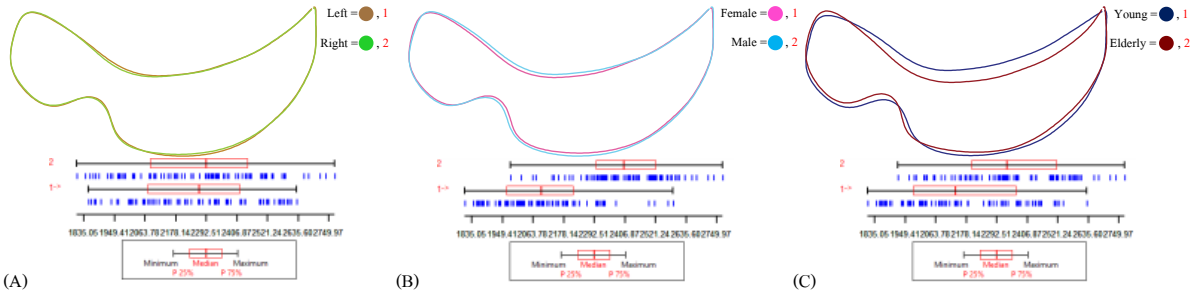

Figure 10 The comparisons of the mean shape and box scale of size of the tubercles (non-articular area) in superior aspect between sides (A), genders (B) and age groups(C)

Discussion and Conclusion

The proximal head of humerus consists of the articular head, greater and lesser tubercles. The articular head appears hemisphere according to anatomical textbook, so far the shape difference of humeral head has not mentioned in any book. The hemispheric humeral head is 3D shape and this study was carried out in 2D image thus it had to take image every aspects of humeral head to represent whole shape. Present study revealed shape difference in all of aspects of humeral head between genders and age groups while side comparison showed no significant difference in all of aspects. These finding coincide with the previous studied that compare shape of articular head between left and right sides in two dimensional outline on superior view using elliptical Fourier functions (EFFs), revealing no

significant difference between sides (Tanaka, 1999). All of aspects of the articular head of the present study showed significant size difference between male which was larger than female. Several linear studied have reported the total length and segments of the humerus in male lager than female. In addition, the humerus and its segments can identify gender of unknown individual especially the vertical head dimension with high accuracy for sex identifications (Steyn et al., 1999; Ali et al., 2016; Iscanet al., 1998). Another studied used Renishaw Cyclone three dimensional device measuring the radius curvature of articular surface that also showed significant difference between male larger than female (Wataru et al, 2005).

The humeral tubercles are non-articular areas that provide attachment for the rotator cuff muscles. Many researchers explored shapes, areas or dimensions of each four footprints of the rotator cuffs on the tubercles (Ruotolo et al., 2004; Curtis et al., 2006; Lazarus and Satyapal, 2016) but recent report of the rotator cuff insertion did not separate but interdigitated to form a singular entity with a common footprint on the humeral tubercles (Vosloo et al., 2017) thus the result of present study that showed shape of whole footprint on each tubercles. The current study investigated shape and size of each humeral tubercles focusing on only whole footprint that appear on them.

The greater tubercle obviously presented supraspinatus, infraspinatus and teres minor footprints on posterior aspect. It is indicated significant difference both in shape and size between genders and age groups. Shape configuration of subscapularis foorprint on lesser tubercle is noticeable on anterior aspect. It is revealed a triangular shape that contrast with Curtis et al. (2006) study that observed on specimen directly but this study investigated on image as two dimensional visualization. Comparative results of subscapularis foorprint on lesser tubercle showed significant shape difference only between genders and showed significant size difference between gender and age groups.

Both tubercles of humeral head are analyzed shape and size on superior view. Shape configuration showed significant difference only between elderly and young but no significant difference between genders and sides. Contrast from study of Tanaka that explored significant bilateral difference in tubercles region of humeral head. They suggested the larger right humerus may be occur greater mechanical loading from the daily activities as the arm dominance (Tanaka, 1999). Size determination of the humeral tubercles on superior view showed significant larger male and elderly group.

The difference between sides of the current study indicated no significant difference both in shape and size. Although, the dominant arm is one of an important external factor that produce greater mechanical force to the bone and may change the shape of the bone (Fresia et al., 1990). In this study showed small difference of shape and size but not significant.

Almost of parameter in geometric morphometric analysis showed significant shape and size difference between male and female. Difference of hormones, muscle activities, greater bone development in male can produce the larger size of the bone in male and build massive and stronger of male muscle than female (Basic et al., 2013; Trinkaus et al., 1994). The contraction of male muscles encourage the more tensile at the insertion site of the bone may lead to mechanical loading to the bone thus small shape change at some part of the bone can occur differently between genders (Kikuchi et al., 2012).

Comparison of the young and elderly specimens revealed the shape and size difference in geometric morphometric analysis. Shape and size of the long bone change throughout of the life, beginning in the embryo with the cartilage formation that gradually becomes replaced with bone. It is made up longitudinally then stops growing in adult known as endochondral ossification (Provot et al., 2008). The date of epiphyseal union of proximal humerus is about sixteen years (Cardoso, 2008) thus all specimens in this study were complete close of epiphyseal plate. The difference of shape and size between specimens aged below 60 years and specimens that above or equal to 60 years was due to an inequality of functional ability and remodeling process in lateral expansion of the bone. The cross sectional geometry of the long bone was adjusted the shape during development by decreasing the deposition on the outer wall and increasing the resorption on the endosteal surface that enhance in bone diameter laterally known as cortical shift. This process occurs rapidly in pre-puberty then stop when the growth plat fusion and raise again in elderly, producing extensive outer dimension and slender cortical wall in aging (Goldman et al., 2009; LaMothe et al., 2003). Concurrently in mice experiment that explored the trabecular bone volume, bone strength and cortical bone size decline with age (Ramanadham et al., 2008) thus the results of this study that elucidated the outline of the elderly bone larger than the young specimens may be expansion of the outer line but cortical bone was thin in the elderly specimen.

Small shape difference between genders and age groups that find in this study may be indicated to difference kinematic (Pearl et al., 1999) causing musculoskeletal disorders and use the shape and size difference for identify the individual in forensic study. Furthermore, the data about shape and size can use to plan the treatment the shoulder problem in difference individual such as the articular prosthetic shape in proximal humeral fracture or repair rotator cuff following its footprint on the greater and lesser tubercles respectively.

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References

Akman ŞD, KarakaŞ P, Bozkir MG. The Morphometric Measurements of Humerus Segments. Turk J Med Sci 2006; 36: 81-5.

Ali DM, Abd Elbaky FAF. Sex identification and reconstruction of length of humerus from its fragments: An Egyptian study. Egyptian Journal of Forensic Sciences 2016; 6: 48-55.

Arias-Martorell J, Tallman M, Potau JM, Bello-Hellegouarch G, Perez-Perez A. Shape analysis of the proximal humerus in orthograde and semi-orthograde primates: correlates of suspensory behavior. Am J Primatol 2015; 77(1): 1-19.

Ashutosha A, Deepali RK, Ajay C, Bahetee BH, Ashish B. Morphometric Analysis and Surgical Anatony of Proximal Humerus. Int J Anat Res 2017; 5(3.1): 4052-62.

Balke M, Schmidt C, Dedy N, Banerjee M, Bouillon B, Liem D. Correlation of acromial morphology with impingement syndrome and rotator cuff tears. Acta Orthop 2013; 84(2): 178-83.

Basic Z, Anteric I, Vilovic K, Petaros A, Bosnar A, Madzar T, et al. Sex determination in skeletal remains from the medieval Eastern Adriatic coast - discriminant function analysis of humeri. Croat Med J 2013; 54(3): 272-8.

Cardoso HF. Age estimation of adolescent and young adult male and female skeletons II, epiphyseal union at the upper limb and scapular girdle in a modern Portuguese skeletal sample. Am J Phys Anthropol 2008; 137(1): 97-105.

Curtis AS, Burbank KM, Tierney JJ, Scheller AD, Curran AR. The insertional footprint of the rotator cuff: an anatomic study. Arthroscopy 2006; 22(6): 603-609.

Fresia AE, Ruff CB, CS. L. Temporal decline in bilateral asymmetry of the upper limb on the Georgia Coast. In Larsen CS, editor. The archaeology of mission Santa Catalina de Guale 2. Biocultural interpretations of a population in transition: anthropological papers of the American Museum of Natural History 1990: 121-50.

Goldman HM, McFarlin SC, Cooper DM, Thomas CD, Clement JG. Ontogenetic patterning of cortical bone microstructure and geometry at the human mid-shaft femur. Anat Rec (Hoboken) 2009; 292(1): 48-64.

Gomez-Valdes JA, Quinto-Sanchez M, Menendez Garmendia A, Veleminska J, Sanchez-Mejorada G, Bruzek J. Comparison of methods to determine sex by evaluating the greater sciatic notch: Visual, angular and geometric morphometrics. Forensic Sci Int 2012; 221(1-3): 156.e1-7.

Greving K, Dorrestijn O, Winters JC, Groenhof F, van der Meer K, Stevens M, et al. Incidence, prevalence, and consultation rates of shoulder complaints in general practice. Scand J Rheumatol. 2012; 41(2): 150-5.

Holliday TW, Friedl L. Hominoid humeral morphology: 3D morphometric analysis. Am J Phys Anthropol 2013; 152(4): 506-15.

Iscan MY, Loth SR, King CA, Shihai D, Yoshino M. Sexual dimorphism in the humerus: a comparative analysis of Chinese, Japanese and Thais. Forensic Sci Int 1998; 98(1-2): 17-29.

Janwantanakul P, Pensri P, Jiamjarasrangsri V, Sinsongsook T. Prevalence of self-reported musculoskeletal symptoms among office workers. Occup Med (Lond) 2008; 58(6): 436-8.

Kikuchi Y, Takemoto H, Kuraoka A. Relationship between humeral geometry and shoulder muscle power among suspensory, knuckle-walking, and digitigrade palmigrade quadrupedal primates. J Anat 2012; 220: 29-41.

LaMothe JM, Hepple RT, Zernicke RF. Selected contribution: Bone adaptation with aging and long-term caloric restriction in Fischer 344 x Brown-Norway F1-hybrid rats. J Appl Physiol (1985) 2003; 95(4): 1739-45.

Lazarus L, Satyapal KS. The Rotator Cuff Footprint: A Cadaveric Study of the Morphometry and Morphology. Int J Morphol 2016; 34(3): 975-85.

Leclerc A, Chastang JF, Niedhammer I, Landre MF, Roquelaure Y, Study Group on Repetitive W. Incidence of shoulder pain in repetitive work. Occup Environ Med 2004; 61(1): 39-44.

Lokanadham S, Khaleel N, Arun Raj P. Morphometric analysis of Humerus bone in Indian population. Sch J App Med Sci 2013; 1(4): 288-90.

Mitteroecker P, Gunz P. Advances in Geometric Morphometrics. Evol Biol 2009; 36: 235-47.

Mochizuki T, Sugaya H, Uomizu M, Maeda K, Matsuki K, Sekiya I, et al. Humeral insertion of the supraspinatus and infraspinatus. New anatomical findings regarding the footprint of the rotator cuff. J Bone Joint Surg Am 2008; 90(5): 962-9.

Pearl ML, Kurutz S. Geometric analysis of commonly used prosthetic systems for proximal humeral replacement. J Bone Joint Surg Am 1999; 81: 660-71.

Pope DP, Croft PR, Pritchard CM, Silman AJ, Macfarlane GJ. Occupational factors related to shoulder pain and disability. Occup Environ Med 1997; 54(5): 316-21.

Provot S, Schipanni E, Wu J, H K. Development of the skeleton. In: Osteoporosis. 3 ed. New York: Academic Press; 2008.

Ramanadham S, Yarasheski KE, Silva MJ, Wohltmann M, Novack DV, Christiansen B, et al. Age-related changes in bone morphology are accelerated in group VIA phospholipase A2 (iPLA2beta)-null mice. Am J Pathol 2008; 172(4): 868-81.

Ruotolo C, Fow JE, Nottage WM. The supraspinatus footprint: an anatomic study of the supraspinatus insertion. Arthroscopy 2004; 20(3): 246-9.

Saha AK. Dynamic stability of the glenohumeral joint. Acta Orthop Scand 1971; 42(6): 491-505.

Sikka A, A. J. Sexual Dimorphism in Humerus: A Morphometric Study in The North Indian Poppulation. International Journal of Basic and Applied Medical Sciences 2016; 6(1): 82-6.

Steyn M, Iscan MY. Osteometric variation in the humerus: sexual dimorphism in South Africans. Forensic Sci Int 1999; 106(2): 77-85.

Sunisa Chaiklienga, Krusuna M. Health risk assessment and incidence of shoulder pain among office workers Procedia Manufacturing 2015; 3: 4841-947.

Tanaka H. Numerical analysis of the proximal humeral outline: Bilateral shape differences. Am J Hum Biol 1999; 11(3): 343-57.

Trinkaus E, Churchill SE, Ruff CB. Postcranial robusticity in Homo. II: Humeral bilateral asymmetry and bone plasticity. Am J Phys Anthropol 1994; 93(1): 1-34.

Urwin M, Symmons D, Allison T, Brammah T, Busby H, Roxby M, et al. Estimating the burden of musculoskeletal disorders in the community: the comparative prevalence of symptoms at different anatomical sites, and the relation to social deprivation. Ann Rheum Dis 1998; 57(11): 649-55.

Vosloo M, Keough N, De Beer MA. The clinical anatomy of the insertion of the rotator cuff tendons. Eur J Orthop Surg Traumatol 2017; 27: 359-66.

Wataru S, Kazuomi S, Yoshikazu N, Hiroaki I, Takaharu Y, Hideki Y. Three-dimensional morphological analysis of humeral heads: a study in cadavers. Acta Orthop 2005; 76(3): 392-6.

Yamamoto A, Takagishi K, Osawa T, Yanagawa T, Nakajima D, Shitara H, et al. Prevalence and risk factors of a rotator cuff tear in the general population. J Shoulder Elbow Surg 2010; 19(1): 116-20.

Zelditch ML, Swiderski DL, Sheets HD, Fink WL. Geometric Morphometrics for Biologists: A Primer USA: Elsevier; 2004.