S ORIGINAL ARTICLE

Shoulder & Elbow

Shoulder & Elbow
2019, Vol. 11(2) 87–93

DOI: 10.1177/1758573217736744
journals.sagepub.com/home/sel
SAGE

Cortical thickness analysis of the proximal humerus

Addie Majed[1], Tanujan Thangarajah[3], Dominic Southgate[2], Peter Reilly[1], Anthony Bull[2] and Roger Emery[1]

Abstract

Background: Structural changes within the proximal humerus influence the mechanical properties of the entire bone and predispose to low-energy fractures with complex patterns. The aim of the present study was to measure the cortical thickness in different regions of the proximal humerus.

Methods: Thirty-seven proximal humeri were analyzed using novel engineering software to determine cortical thickness in 10 distinct anatomical zones.

Results: The cortical thickness values ranged from 0.33 mm to 3.5 mm. Fifteen specimens demonstrated a consistent pattern of progressive cortical thinning that increased between the bicipital groove (thickest), the lesser tuberosity and the greater tuberosity (thinnest). Fifteen humeri were characterized by a progressive increase in cortical thickness between the greater tuberosity (thinnest), the bicipital groove and lesser tuberosity (thickest). The diaphysis exhibited the thickest cortical zone in 27 specimens, whereas the articular surface possessed the thinnest cortex in 18 cases.

Conclusions: In conclusion, this is the first study to comprehensively assess cortical thickness of the humeral head. Our findings suggest that proximal humeral fractures occur along lines of cortical thinning and are displaced by the hard glenoid bone. The identification of specific areas of thick cortices may improve pre-operative planning and optimize fracture fixation.

Keywords

biomechanical modelling; cortical thickness, fracture patterns; proximal humeral fracture

Date received: 8th March 2017; revised: 24th May 2017; accepted: 21st September 2017

Introduction

Fractures of the proximal humerus often occur as a result of either direct impact or muscular pull on a region of cortical weakness.[1] Complex fracture patterns are characterized by involvement of the tuberosity fragments, with the greater tuberosity most commonly being affected.[2] One such example is the four-part fracture in which a small segment of the greater tuberosity remains attached to the hard bone of the bicipital groove and, via the groove, to the lesser tuberosity.[2]

Cortical bone is integral to the mechanical strength of bone, with good correlation demonstrated between bone density and compressive strength.[3–5] Peripheral quantitative computerized tomography (pQCT) has been used in the human radius to assess cortical bone under compressive forces and this has shown that mineral content is predictive of compressive strength.[6] However, there are few reports examining cortical thickness and density of the proximal and distal humerus.[7–9]

Several techniques have been used to assess bone quantity and quality of the proximal humerus. Tingart et al.[7] evaluated the bone mineral density (BMD) of the proximal humerus and demonstrated that it was 18% higher in the surgical neck compared

[1]Division of Surgery and Cancer, Imperial College London, London, UK
[2]Department of Bioengineering, Imperial College London, London, UK
[3]Shoulder and Elbow Service, Royal National Orthopaedic Hospital, London, UK

Corresponding author:
Addie Majed, Division of SORA (Surgery Oncology Reproductive Medicine and Anaesthetics), Imperial College London, 10th Floor QEQM Building, St Mary's Hospital, Praed Street, London W2 1NY, UK.
Email: a.majed@doctors.org.uk

to the humeral head and 30% less in the greater tuberosity compared to the lesser tuberosity. Tingart et al.[10] additionally assessed the three-dimensional distribution of BMD in the proximal humerus using pQCT by calculating the total trabecular and cortical volumetric bone mineral densities (vBMD). The proximal part of the head had a significantly greater trabecular and cortical vBMD than the distal part and the cortical vBMD of the articular surface was significantly lower than that of the tuberosities. Other studies have evaluated the histomorphometry and bone strength distribution of the proximal humerus and found the lowest BMD to be in the central portion and in the tuberosities.[11]

Proximal humerus fractures often occur in osteoporotic bone in which there is endosteal-diaphyseal resorption and medullary expansion.[12] These changes in diameter of the inner and outer cortices influence bending and torsional properties of the entire bone and predispose to low-energy fractures with complex patterns.[13] Fracture configuration has typically been attributed to the position of the shoulder at the time of impact and the overall strength/quality of the primal humeral bone.[2] In the case of four-part fractures of the proximal humerus, the primary fracture line was suggested to bypass the hard bone of the bicipital groove where it is re-directed by the glenoid to the softer bone of the greater tuberosity (lateral to the supraspinatus facet), finally culminating with a lesser tuberosity injury.[2]

Although much work has been published examining patterns of trabecular bone quality, there is a paucity of data evaluating cortical bone distribution and thinning of the proximal humerus, as well as how the microstructure of the proximal humerus determines fracture evolution. Thus, the purpose of the present study was to measure the cortical thickness in different regions of the proximal humerus.

Materials and methods

Study design

Prior to commencement of the present study, local ethical approval was obtained. Thirty-eight unpaired anonymous skeletally mature shoulders were used with no data regarding age or sex available. Fresh frozen specimens were stored at −20 °C and then thawed at room temperature for at least 12 h before preparation and testing. All soft tissue attachments were removed from the bone except the joint capsule.

Each shoulder underwent computed tomography (CT) scanning performed on a Philips Brilliance 64 multi-scanner (Koninklijke Philips NV, Eindhoven, The Netherlands) using high dosage (300 mAs) and a slice thickness of 0.67 mm. The data output was converted to pixels to allow the CT image to be transformed into one defined by relative radiodensity. The primary image plane was axial with a 180 mm × 180 mm restricted field of view to focus on the shoulder. Reformatting was performed using a Philips bone algorithm with a slice thickness of 0.33 mm, such that overall voxel size was 0.324 mm × 0.324 mm × 0.33 mm. This aimed to achieve the most detailed fine cut images available in the clinical setting. Furthermore, the thin slices and reformatting aimed to reduce partial volume effect.

Testing protocol

The CT scan dicom data were imported into MIMICS 11.0 (Materialise, Leuven, Belgium) software and then underwent thresholding using the software package predetermined cortical bone window values (Figure 1). The segmented bone was transformed into a Stereo Lithograph (STL) file. All specimens were checked for defects so that any defects of the STL attributed to partial volume effect were corrected to ensure the minimum

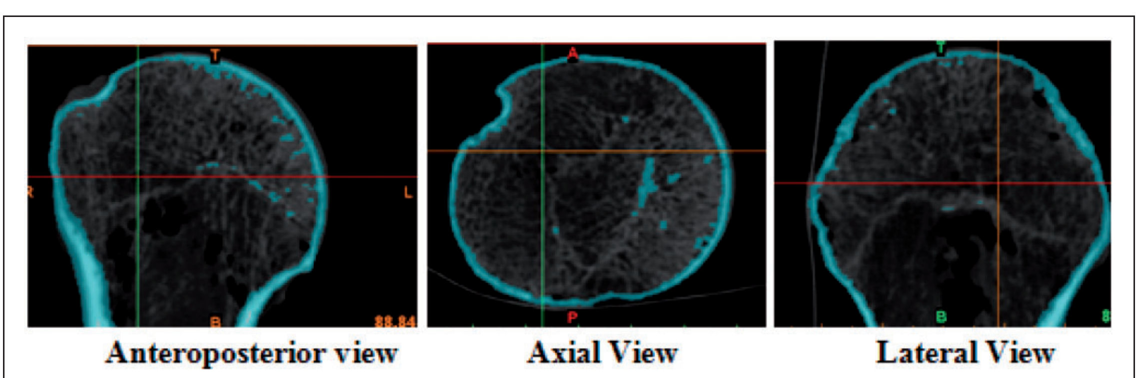

Figure 1. Anteroposterior, axial and lateral computed tomgraphy scan slices with thresholding of intact proximal humeral bone demonstrating cortical bone thresholding (blue).

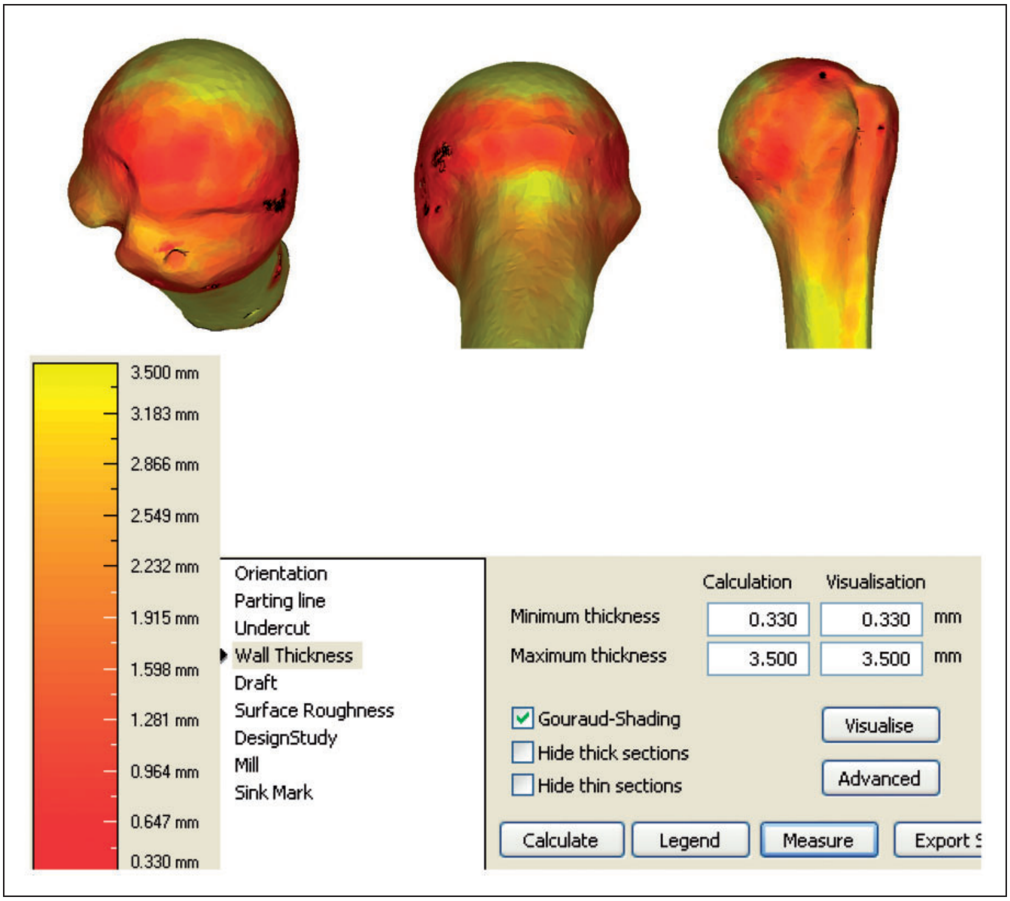

Figure 2. Caudal, cranial and anteroposterior views of a standard lithograph file of a humerus after wall thickness analysis. Yellow denotes thick regions and red denotes thin regions.

pixel thickness would represent any present bone. The minimum possible measurable cortical thickness, dictated by the CT slice thickness and reformatting (0.33 mm), was applied to these defects.

The STL file was extracted into Magics 12.11 (Materialise) to analyze thickness of the object using a Wall Thickness Analysis Tool (Materialise). The minimum threshold was set at 0.33 mm (the smallest possible pixel size) and the maximum thickness was set at 3.5 mm. Areas of maximum thickness were denoted by progressively darker shades of yellow (darker shades for the thickest areas), whereas thinner areas were identified by progressively darker shades of red (darker shades for the thinnest areas) Figure 2.

The humerus was divided into 10 zones from where 10 readings of cortical thickness (mm) were taken (Figure 3):

- Humeral head – central zone (HH)
- Lesser tuberosity (LT)
- Greater tuberosity (GT)
- Bicipital groove (BG)
- Articular margin – anterior (AMA)
- Articular margin – posterior (AMP)
- Articular margin – medial superior (AMMS) ($\leq$1 cm above the articular margin)
- Articular margin – medial inferior (AMMI) ($\leq$1 cm below the articular margin)
- Metaphyseal region (MET)
- Diaphyseal region (DIAPH)

Statistical analysis

Thicknesses in the regions of interest were tabulated. All data were transformed from thickness in millimetres to a relative cortical thickness by dividing the result by the thickest possible value (3.5 mm) to universally represent the cortical thickness zone relative in all the humeri, aiming to eliminate variations in distribution that may have been age and sex-related.

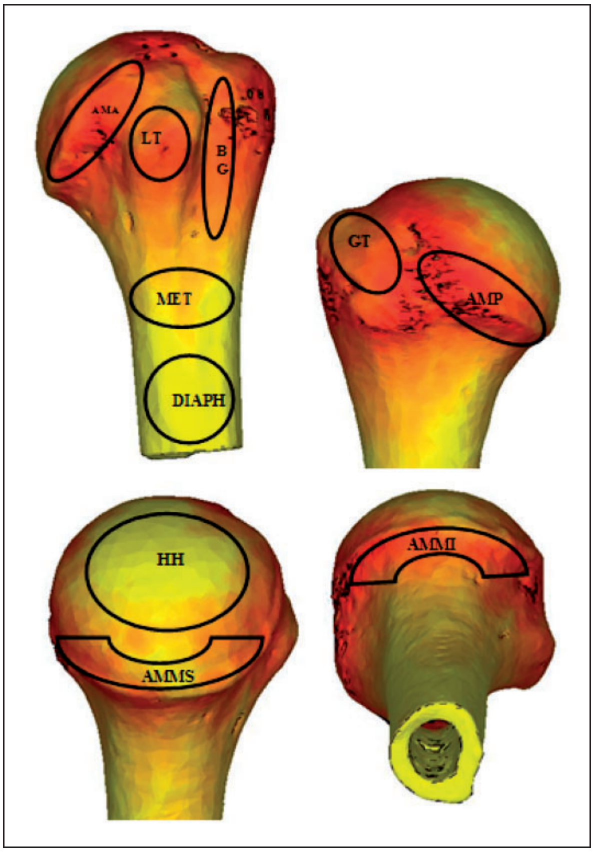

Figure 3. Zones of cortical thickness.

Results

One shoulder was excluded because the diaphysis contained a tumour-like lesion. This left 37 humeri for analysis of which 17 were left sided and 20 were sided. The cortical thickness values ranged from 0.33 mm to 3.5 mm. The resultant relative cortical thickness values ranged from 0.094 to 1.0 (with 1.0 representing 3.5 mm or maximal thickness).

Relationship between the tuberosities and the bicipital groove

Two predominant patterns emerged when assessing the relationship between the lesser and greater tuberosity (Table 1): (i) 15/37 humeri demonstrated a consistent pattern of cortical thinning that progressively increased between the bicipital groove (thickest), the lesser tuberosity, and the greater tuberosity (thinnest) (Figure 4) and (ii) 15/37 humeri were characterized by a progressive increase in cortical thickness between the greater tuberosity (thinnest), the bicipital groove, and the lesser tuberosity (thickest) (Figure 5).

In four specimens, the cortical zone was the thinnest in the lesser tuberosity and thickest in the bicipital groove and, in two further specimens, the greatest cortical thickness was observed in the lesser tuberosity, followed by the greater tuberosity and the bicipital groove (thinnest). In the remaining sample, the greater tuberosity exhibited the thickest cortex followed by the bicipital groove and the lesser tuberosity (thinnest).

Table 1. Relative cortical thickness of the bicipital groove (BG), lesser tuberosity (LT) and greater tuberosity (GT).

Cortical thickness patterns	Number of specimens
BG > LT > GT	15/37
LT > BG > GT	15/37
BG > GT > LT	4/37
LT > GT > BG	2/37
GT > BG > LT	1/37

Relationship between the proximal humerus and the diaphysis

In the majority of specimens (25/37), cortical thickness increased between the humeral head (thinnest), metaphysis and the diaphysis (thickest) (Table 2) (Figure 5). The diaphysis exhibited the thickest cortical zone in 27/37 specimens. Four remaining patterns were observed between the humeral head, metaphysis and the diaphysis (Table 2).

Articular margin relationships

The cortical zone in the four regions examined on the articular surface was thinner than in all other areas in 18/37 cases. In these specimens, the superior articular margin was the thickest and, in seven specimens, the inferior articular margin was the thickest (Table 3) (Figure 6).

In 22 specimens, the cortical zone of the posterior articular margin was either the thinnest or equal thinnest with an adjacent region (Figure 6). The medial inferior AMMI was thinnest in five cases compared to the superior AMMS, which was the thinnest zone in only two cases. By contrast, the anterior articular margin was thinnest in four specimens. In three of 37 specimens, the cortex was the thinnest in the greater tuberosity and, in one specimen, it was the thinnest in the lesser tuberosity.

Discussion

The present study is the first of its kind to describe the distribution of cortical thinning around the proximal

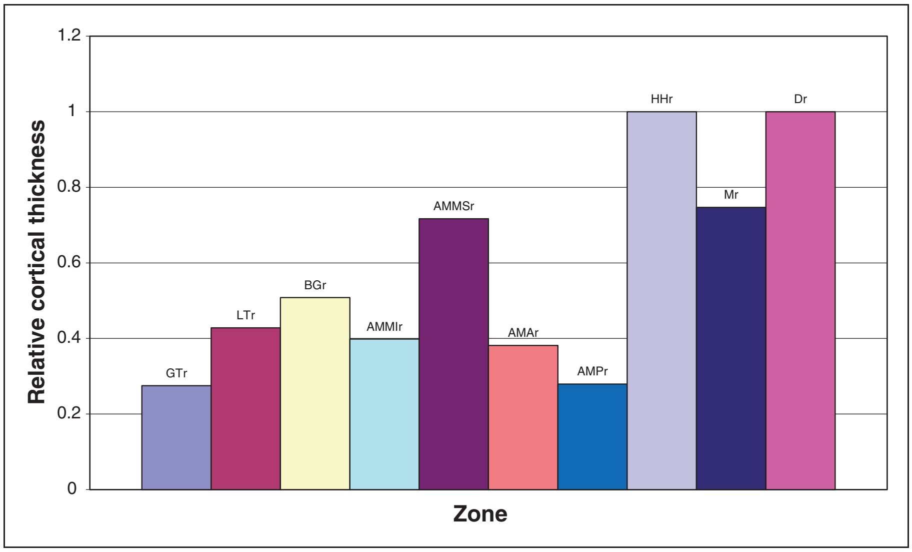

Figure 4. Histogram of specimen 1 demonstrating relative cortical thickness relationship bicipital groove (BG) > lesser tuberosity (LT) > greater tuberosity (GT) of the proximal humerus.
GTr = Greater tuberosity region; LTr = Lesser tuberosity region; BGr = Bicipital groove region; AMMIr = Articular margin-medial inferior region; AMMSr = Articular margin-medial superior region; AMAr = Articular margin anterior region; AMPr = Articular margin posterior region; HHr = Humeral head region; Mr = Metaphyseal region; Dr = Diaphyseal region.

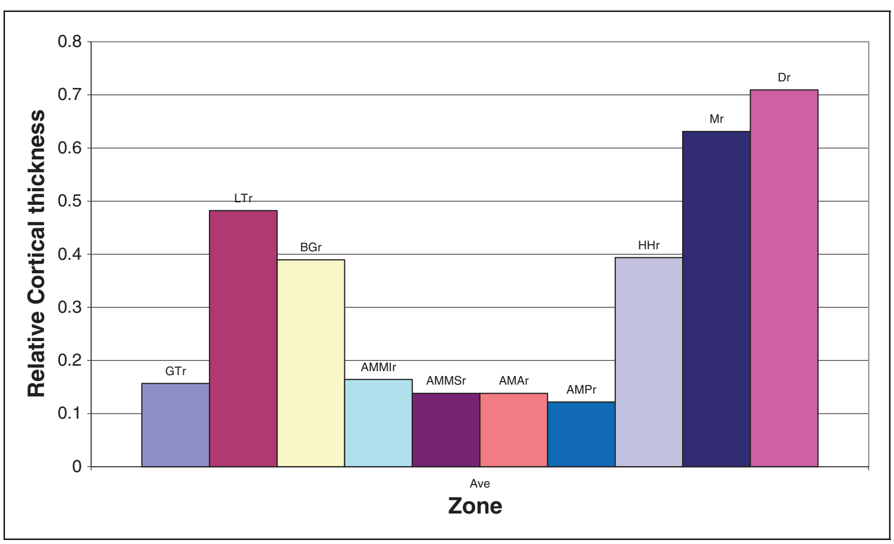

Figure 5. Histogram of specimen 7 demonstrating relative cortical thickness relationship lesser tuberosity (LT) > bicipital groove (BG) > greater tuberosity (GT) of the proximal humerus.
GTr = Greater tuberosity region; LTr = Lesser tuberosity region; BGr = Bicipital groove region; AMMIr = Articular margin-medial inferior region; AMMSr = Articular margin-medial superior region; AMAr = Articular margin anterior region; AMPr = Articular margin posterior region; HHr = Humeral head region; Mr = Metaphyseal region; Dr = Diaphyseal region.

humerus. We speculate that these areas may act as planes of weakness and determine the progression of fracture lines and therefore fracture configuration. Edelson et al.[2] suggested that the hard-packed bone of the glenoid persists throughout senescence and acts as an anvil against which the humeral head abuts. This can result in two-part fractures with the primary fracture line occurring through the relatively weak articular margin (Figures 2 and 3). This area was denoted as the AMMI (articular margin – medial inferior) zone in the present study, and possessed the thinnest cortex in five cases in addition to being adjacent to the AMP

(articular margin – posterior) zone, which had the thinnest cortex in 22 cases. Under compression, fractures may propagate along these regions and result in angulation deformities. Alternatively, tensile loads may cause a shield-type injury with maintenance of tuberosity position and glenoid shearing of the articular surface into valgus.

Cortical thickness was lower in the greater tuberosity than in the lesser tuberosity and bicipital groove in the majority of specimens. This is integral to the occurrence of four-part fractures where the thicker bicipital groove retains the lesser tuberosity and a fragment of the thinner greater tuberosity. In this, the intact bone of the bicipital groove protects the arcuate vessels. Tamai et al.[14] described a fracture pattern characterized by the lesser tuberosity being attached to the shaft, an isolated greater tuberosity fragment and a humeral head devoid of all soft tissue attachments. This distinct arrangement can be explained by the findings in the present study where, in 15 cases, the lesser tuberosity had the greatest cortical thickness and the greater tuberosity had the least. Accordingly, the thin articular margin would have adopted a position of valgus, the thin greater tuberosity would have fractured and been retracted by the rotator cuff, and the thick lesser tuberosity and bicipital groove would have remained attached to the metaphysis.

Shield fractures are considered to represent a continuation of more simple fracture patterns.[2] In the simpler two-part injuries, the primary fracture line occurs through the surgical neck alone. In three-part injuries, in addition to the surgical neck, the greater tuberosity is involved. As the fracture line progresses, it detaches the greater tuberosity from the humeral head and continues forward to incorporate the superior aspect of the

Table 2. Relative cortical thickness of the diaphysis (DIAPH), metaphysis (MET) and humeral head (HH)

Cortical thickness patterns	Number of specimens
DIAPH > MET > HH	25/37
DIAPH > HH > MET	4/37
MET > HH > DIAPH	2/37
HH > DIAPH > MET	2/37
MET > DIAPH > HH	4/37

Table 3. Relative cortical thickness of the articular margin posterior (AMP), articular margin anterior AMA), articular margin medial inferior (AMMI) and articular margin superior (AMMS)

Thinnest cortical zone	Number of specimens
AMP	22/37
AMMI	5/37
AMA	4/37
AMMS	2/37

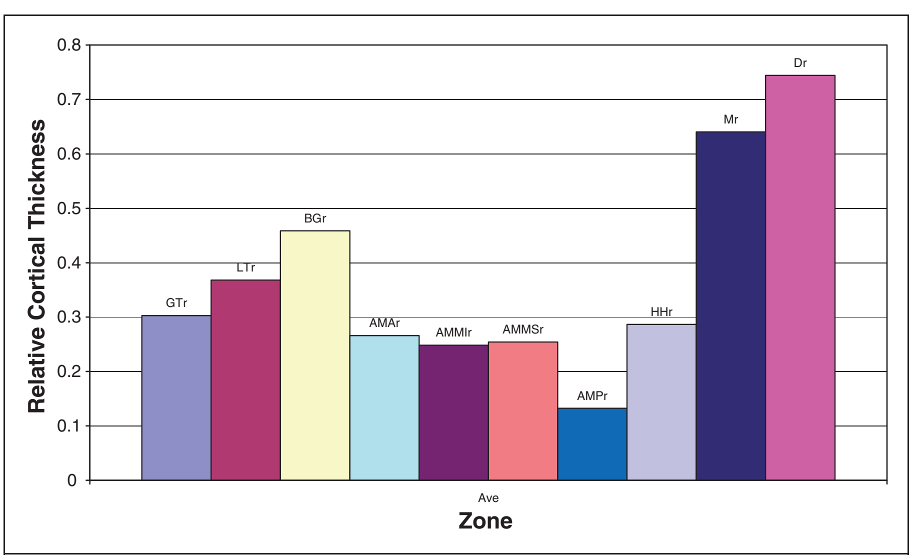

Figure 6. Histogram of specimen 9 demonstrating relative cortical thickness relationship of the articular margin of the proximal humerus.
GTr = Greater tuberosity region; LTr = Lesser tuberosity region; BGr = Bicipital groove region; AMMIr = Articular margin-medial inferior region; AMMSr = Articular margin-medial superior region; AMAr = Articular margin anterior region; AMPr = Articular margin posterior region; HHr = Humeral head region; Mr = Metaphyseal region; Dr = Diaphyseal region.

bicipital groove and the lesser tuberosity.[2] In these three-part fractures, it has been speculated that the greater tuberosity develops internal comminution, a feature that can be attributed to its thin cortex. Furthermore, the observation that the cartilaginous head is sheared off from the 'Shield' by the glenoid and subsequently tilts posteriorly into varus or valgus may be explained by the marked cortical thinning around the articular margin. Varus deformities typically result from thinning of the medial articular margin; however, the majority of cortical thinning in the present study was found at the posterior aspect of the articular margin and would account for the posterior angulation identified in two- and three-part fractures.[2]

The articular margin was the thinnest region of the proximal humerus in the majority of specimens (18/37). This may predispose to valgus impaction fractures as the articular surface is sheared off, leaving the thicker humeral head intact and in a position of valgus by the neighbouring glenoid. As a result of the thicker cortical bone in the metaphysis, the fracture line may not extend any further and alter the existing injury pattern.

Limitations of the present study include the number of specimens used, technical problems encountered from partial volume effect, as well as the inability to account for age and sex differences. To provide more information, a comparative study assessing the outcome using pQCT would be useful, as would a comparison between cortical thickness and cortical mineral density.

In conclusion, this is the first study to use novel engineering software to assess cortical thickness of the humeral head. Our findings suggest that proximal humeral fractures occur along lines of cortical thinning and undergo displacement according to their muscular attachments and the effect of hard glenoid bone. The identification of specific areas of thick cortices may improve pre-operative planning and optimize fracture fixation. In doing so, the risks of implant failure and loosening may be reduced, and patient outcome may improve.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Ethical review and patient consent

Not required for this article.

References

1. Neer CS II. Displaced proximal humeral fractures. I. Classification and evaluation. *J Bone Joint Surg Am* 1970; 52: 1077–1089.
2. Edelson G, Kelly I, Vigder F and Reis ND. A three-dimensional classification for fractures of the proximal humerus. *J Bone Joint Surg Br* 2004; 86: 413–425.
3. Mazess RB. Fracture risk: a role for compact bone. *Calcif Tissue Int* 1990; 47: 191–193.
4. Beck TJ, Ruff CB, Warden KE, Scott WW Jr and Rao GU. Predicting femoral neck strength from bone mineral data. *A structural approach*. Invest Radiol 1990; 25: 6–18.
5. Dempster DW, Ferguson-Pell MW, Mellish RW, et al. Relationships between bone structure in the iliac crest and bone structure and strength in the lumbar spine. *Osteoporis Int* 1993; 3: 90–96.
6. Louis O, Boulpaep F, Willnecker J, Van den Winkel P and Osteaux M. Cortical mineral content of the radius assessed by peripheral QCT predicts compressive strength on biomechanical testing. *Bone* 1995; 16: 375–379.
7. Tingart MJ, Apreleva M, von Stechow D, Zurakowski D and Warner JJ. The cortical thickness of the proximal humeral diaphysis predicts bone mineral density of the proximal humerus. *J Bone Joint Surg Am* 2003; 85: 611–617.
8. Diederichs G, Issever AS, Greiner S, Linke B and Korner J. Three-dimensional distribution of trabecular bone density and cortical thickness in the distal humerus. *J Shoulder Elbow Surg* 2009; 18: 399–407.
9. Diederichs G, Korner J, Goldhahn J and Linke B. Assessment of bone quality in the proximal humerus by measurement of the contralateral site: a cadaveric analyze. *Arch Orthop Trauma Surg* 2006; 126: 93–100.
10. Tingart MJ, Bouxsein ML, Zurakowski D, Warner JP and Apreleva M. Three-dimensional distribution of bone density in the proximal humerus. *Calcif Tissue Int* 2003; 73: 531–536.
11. Hepp P, Lill H, Bail H, et al. Where should implants be anchored in the humeral head? *Clin Orthop Rel Res* 2003; 139–147.
12. Seeman E, Bianchi G, Adami S, Kanis J, Khosla S and Orwoll E. Osteoporosis in men – consensus is premature. *Calcif Tissue Int* 2004; 75: 120–122.
13. Giannoudis PV and Schneider E. Principles of fixation of osteoporotic fractures. *J Bone Joint Surg Br* 2006; 88: 1272–1278.
14. Tamai K, Hamada J, Ohno W and Saotome K. Surgical anatomy of multipart fractures of the proximal humerus. *J Shoulder Elbow Surg* 2002; 11: 421–427.