Analysis of Fracture Distribution in the Surgical Neck Region of the Proximal Humerus: a 3D Bone Cortical Thickness Mapping Study

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Research

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Abstract

Objection: Among the many studies on the proximal humerus, few have focused on cortical bone distribution around the surgical neck region and its relationship with the epiphysis.

Materials and methods: Ninety-five surgical neck fracture patients with available plain X-rays and CT scans were enrolled. In addition, 38 normal subjects were also included to illustrate the cortical thickness of the diaphysis, cortical change region and greater tuberosity.

Results: The fracture lines were mainly distributed in the cortical change region. Significant differences were found in cortical thickness between the diaphysis, surgical region and greater tuberosity in men and women. The thickest cortex was noted in the diaphysis, and the thinnest cortex was noted in the greater tuberosity. No significant differences were observed in the width of the cortical change region in man and women.

Conclusion: The surgical neck region had decreased cortical thickness. It was concluded that the epiphysis connection region had an effect and acted on the proximal humeral fracture pattern in adults; therefore, the surgical neck fracture was identified as an epiphyseal relative fracture.

Background

Proximal humeral fracture (PHF) affects patient health and accounts for approximately 4 to 5% of traumatic fracture hospital admissions [1, 2]. Proximal humeral fractures, which are consistently investigated as osteoporotic fractures, are a health priority and might impose a great burden on medical costs in China [3-5]. It was reported that PHF occurs as a result of impact or muscular pull on the region of cortical weakness [6]. Cortical bone is integral to the mechanical strength of bone, and a good correlation has been demonstrated between bone density and strength. Since Barnett investigated the relationship between cortical bone thickness and bone mineralization in 1960, increased accuracy for estimation of bone mineral density was realized with the advancement of digital radiographic technologies, which significantly increased the speed and precision for measuring cortical bone thickness.

The outer cortical bone is considered a key determinant of bone strength and fracture risk [7, 8]. The usefulness of cortical bone thickness measurements is investigated at multiple anatomic sites with many methods, such as X radiographs and peripheral quantitative computerized tomography [9]. Increasing evidence has illustrated that focal structural weaknesses may predispose patients to fragile fractures [10, 11]. Cortical bone carries a considerable share of the total load of the skeleton in the proximal humerus [5, 12]. Studies focusing on the humerus have yielded promising results for the use of cortical bone thickness, which illustrated a strong association between radiographic cortical bone thickness and local mineral content [13].

In most research on the proximal humerus, the 4-segment theory is typically used to describe the proximal humerus and relative injuries [14, 15]. According to the Neer classification, 28% of patients have two-part fractures, which mostly occur in patients over 50 years old [16, 17]. Among many studies on the proximal humeri, few reports have focused on the cortical bone distribution around the surgical neck region and the relationship with the epiphysis in children. The aim of the research was to illustrate the characteristics of cortical thickness and fracture line distribution surrounding the surgical neck region with 3D cortical bone mapping and try to find the relationship between fractures and the epiphysis when they were young.

Materials And Methods

In this retrospective study (NCT04523415), the data of patients diagnosed with proximal humerus fractures and people without fractures were evaluated in one orthopaedics centre from 2015.1-2019.12, and the last 95 CT scans of proximal humeral surgical neck fractures were collected to illustrate the fracture distribution. Thirty-eight normal people with intact proximal humerus were enrolled to measure cortical thickness. All anonymous data were evaluated. Ethical approval was obtained from the Regional Ethics Committee of the Third Hospital of Hebei Medical University, and the study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all patients enrolled in the study.

The inclusion criteria were as follows: (i) clear records of demographic data; (ii) complete initial X-ray and CT imaging data; and (iii) patients older than 18 years. The exclusion criteria for the study were as follows: (i) patients with the presence of neurological disease (syringomyelia) and (ii) open or pathological fractures (tumour , etc.).

Participants were scanned in the clinical while-body multidetector computerized tomography machine (120 kV, 170 mAs, ≤ 1 mm reconstructed slice thickness, and Siemens SOMATATION sensation 64). The subjects were divided into two different groups (males and females).

Proximal humeral templates

The series of DICOM images were received in our hospital via PACS (ICZ, Brno, Czech Rep.) and were subsequently reconstructed to identify the fracture pattern. The CT scan DICOM data were imported into Mimics 20.0 (Materialise, Leuven, Belgium), and thresholding function was conducted with the software package predetermined cortical bone window value. In this research, Hounsfield units of 226 (minimum) and 1600 (maximum) were used as the threshold of the bone tissue.

Lateral images of the 3D proximal humerus were exported from the Mimics medical workstation. Using Mimic with B30 CT data, the 3D construction was then exported directly to 3 Matic 12.0 (Materialise, Leuven, Belgium). The wall thickness analysis tool was used to analyse the cortical thickness. The minimum threshold was set at 0.33 mm (the smallest possible pixel size), and the maximum thickness was set at 10 mm. Then, the cortical thickness images (2D) were imported into Adobe Illustrator and identified as the templates for the surgical neck fracture model.

Fracture distribution in cortical thickness map

Thirty-four men (47.2 ± 17.6 years) and 61 women (62.0 ± 14.5 years) who were diagnosed with proximal humeral surgical neck fractures in the clinic were enrolled. The 3D reconstruction images were obtained using the Radioant DICOM reviewer, and the fracture line was observed clearly.

The fracture lines were simulated and transcribed freehand onto the templates to illustrate the surgical neck fractures in the established template. For ease of analysis, small areas of relatively high comminution fractures were simplified as single fracture lines. To optimize the accuracy of this procedure, the transcriptions were performed by the first and second authors and were reassessed by an additional two trauma surgeons. Any discrepancies between the reviewers were reassessed, and the final results were identified by experienced surgeons after a comprehensive evaluation.

The local cortical thickness can be observed from the cortical thickness map in each normal person, and the relationship with the surgical neck region is illustrated in the template.

Cortical thickness measurement

Normal people without fractures, including 23 men (46.1±11.1 years) and 15 women (50.8 ±18.1 years), were enrolled to measure the cortical thickness of the greater tuberosity, surgical neck region and diaphysis.

□. The line located under the lesser tuberosity was chosen as the plane to measure the cortical thickness of the surgical neck region. Three points were selected adjacent to the bicipital groove (anterolateral), middle of the greater tuberosity and posterolateral point. □. The line located at the top of the lesser tuberosity was chosen as the plane to measure the cortical thickness of the surgical neck region. Three points were selected adjacent to the bicipital groove (anterolateral), middle of the greater tuberosity and posterolateral point. III. The line that was parallel and had the same distance from the above line to the first line was chosen as the plane to measure the cortical thickness of the diaphysis (Figure 1). Finally, the average value of three locations was used as the final measurement result. Furthermore, the width (the distance between the proximal and distal directions) of this surgical neck region was measured and illustrated (Figure 2).

Statistical analysis

Continuous data are presented as the means with standard deviation. Mann-Whitney U tests were conducted for comparisons between the 2 independent groups, and Kruskal-Wallis H tests were used to conduct comparisons among 3 independent groups. In addition, x^2 tests were used to evaluate categorical variables. Homogeneity of variance for continuous variables was evaluated using the Levene test for equality of variances. For all analyses in this research, significance was set at the $P < 0.05$ level. Before data analysis, statistical significance was set at $P = 0.05$. All analyses were conducted using SPSS Version 22.0 (IBM Corp, Armonk, NY).

Results

Fracture distribution in cortical thickness map

The differences in fracture distribution in males and females are displayed on an average right proximal humerus surface map using a colour scale. The fracture lines were mainly distributed in the cortical change region (which was identified as the surgical neck region). The fracture lines were more complicated in women than in men as observed in the cortical thickness map (Figs. 3 and 4).

Cortical thickness measurement

Significant differences were found in cortical thickness between the diaphysis, surgical region and greater tuberosity in men ($P < 0.001$) and women ($P < 0.001$). There was the thickest cortex in the diaphysis region (man, 3.73 ± 0.59 mm vs woman 2.86 ± 0.65 mm; $P < 0.001$) and the thinnest cortex in the greater tuberosity region (man, 1.40 ± 0.24 mm vs woman 1.16 ± 0.40 mm; $P = 0.048$). The cortical thickness in the cortical change region was 2.46 ± 0.36 mm in men and 1.88 ± 0.58 mm in women ($P = 0.001$) (Fig. 5).

The mean width of the cortical change region was 7.61 ± 1.45 mm in men compared with that in women (7.3 ± 2.51 mm). No significant differences were observed in the width of the cortical change region ($P = 0.754$).

Discussion

The 3D bone mapping used in this study illustrated the differences in fracture line distribution and cortical thickness in the surgical neck region of the proximal humerus. The map displays various cortical thicknesses with different colours and is sufficiently sensitive to illustrate small differences due to several thousand independent measurements across each proximal humerus. The present study is the first of its kind to describe the distribution of fracture lines and cortical thickness around the surgical neck over the surface of the proximal humerus with a cortical thickness map. It was found that the surgical neck region had a relatively thinner cortical thickness than the diaphyseal region of the humerus, and surgical neck fracture lines were mainly observed in this special region. The research also illustrated a consistency between cortical thickness and fracture line distribution in the surgical neck region. The surgical neck region with decreased cortical thickness existed and was still observed even after supposed skeletal maturation.

Skeletal maturation is a proxy for biological maturation and is important for a variety of clinical and forensic purposes. The proximal humeri was the last part of epiphyseal closure conversion in the appendicular skeleton [18]. The coalescence between the epiphysis and diaphysis (16–18 years old) is relatively late compared with the epiphysis of the greater and lesser tuberosity. In accordance, a difference in cortical thickness in the surgical neck region was noted compared with other adjacent structures by cortical thickness mapping. Furthermore, decreased humeral cortical bone thickness is closely associated with a low BMD [19]. Therefore, cortical thickness changes may be one of the reasons

for commonly observed surgical neck fractures in all age groups of patients. However, no studies have identified the extent of the surgical neck region and its morphological characteristics, such as cortical thickness, compared with other important structures in the proximal humerus. Based on the fracture line distribution method used in previous research, the study demonstrates that most of the fracture lines diagnosed as surgical neck fractures in the clinic are mainly distributed in the cortical change region on the template along with other measurements of the cortical thickness in our research. We had sufficient evidence to identify the cortical change region as the surgical neck region [15].

In our study, the surgical neck region was measured with Mimic, and cortical thickness was compared with other important anatomic regions, such as the greater tuberosity or diaphysis. The results demonstrated that the connected region of diaphysis and humeral head had a step change of cortical thickness, and the cortical thickness in surgical neck region was obviously thinner than that of diaphysis and thicker than that of the greater tuberosity, which was directly connected with the surgical neck region. Therefore, a relatively weak region formed definitely, and it still existed regardless of age (Fig. 6). In the lateral view, the shape of this region was more like a lipid bilayer with unshaped spindrift running gradually to both sides of the greater tuberosity. It changes in the long period just like its shape without regular morphology, and the width or square may decrease as people age and osteoporosis appears. Therefore, research on the surgical neck region is important and helpful to identify a substantial correlation between fractures and the epiphysis, and osteoporosis is not the only physiological reason for fractures.

The precise sites of focal osteoporosis that we have now identified are consistently overlooked by current 2D bone densitometry methods. The identification of original cortical thickness in specific areas may improve preoperative planning and optimize fracture fixation. Another important contribution of this research was that connection regions exist between the greater and lesser tuberosity (bicipital groove fracture), greater and humeral head, and lesser and humeral head. The main reason for this phenomenon was the step union of the epiphysis. The earlier the union of the epiphysis, the thicker the connection region. The union time of greater and lesser tuberosity was 3–5 years old, greater or lesser tuberosity and humeral head was 4–8 years old, and proximal humeral epiphysis and diaphysis was 16–18 years old [20]. It was hypothesized that the main fracture line was also more inclined to occur around these connection regions. Although no comparison was performed regarding the cortical thickness in these connection regions, the hypothesis about the relationship between the epiphysis and fracture lines was beneficial for understanding the origin of fractures under different injury mechanisms. Supported by this research on the relationship between surgical neck fracture and epiphysis, the concept of epiphyseal relative fracture was proposed.

Limitations were placed on the number of subjects enrolled, and more patients will be included in our future work. The anatomic bone structure and muscles terminations of surgical neck region was not fully illustrated. In further studies, cortical thickness changes in the lesser tuberosity and bicipital groove will be assessed, and the width of the surgical neck region will be discussed further. Questions, such as whether the fracture was more likely to occur in, out or around the connection region, will be further

studied to identify a clearer relation between the epiphysis and fracture line distributions. In our subsequent research, simple fractured CT will be constructed to identify epiphyseal fractures.

In conclusion, this study was the first to identify the morphological characteristics of the surgical neck region in adults. It was beneficial to understand the formation of the surgical neck region and the relationship with the epiphysis. It was concluded that the epiphysis connection region had an effect and still acted on the proximal humeral fracture pattern in adults. More work should be conducted to reveal the newly proposed concept of epiphyseal relative fractures.

Declarations

Ethics approval and consent to participate

Ethical approval was received from the Regional Ethics Committee of the Third Hospital of Hebei Medical University, and the study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all patients enrolled in the study.

Consent for publication

All authors and participants are consent for publication.

Competing interests

The authors have declared that no competing interests exist.

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Authors' contributions

Conceptualization: Yingze Zhang.

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Formal analysis: Weichong Dong.

Investigation: Yali Zhou, Zhongzheng Wang.

Methodology: Jialiang Guo.

Project administration: Jialiang Guo, Yali Zhou.

Resources: Yingze Zhang, Weichong Dong

Software: Jialiang Guo.

Supervision: Zhiyong Hou, Yingze Zhang.

Validation: Zhiyong Hou, Yingze Zhang.

Visualization: Zhiyong Hou.

Writing – original draft: Jialiang Guo.

Writing – review & editing: Jialiang Guo.

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Availability of data and material

All relevant data can be obtained for the corresponding email address.

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Figures

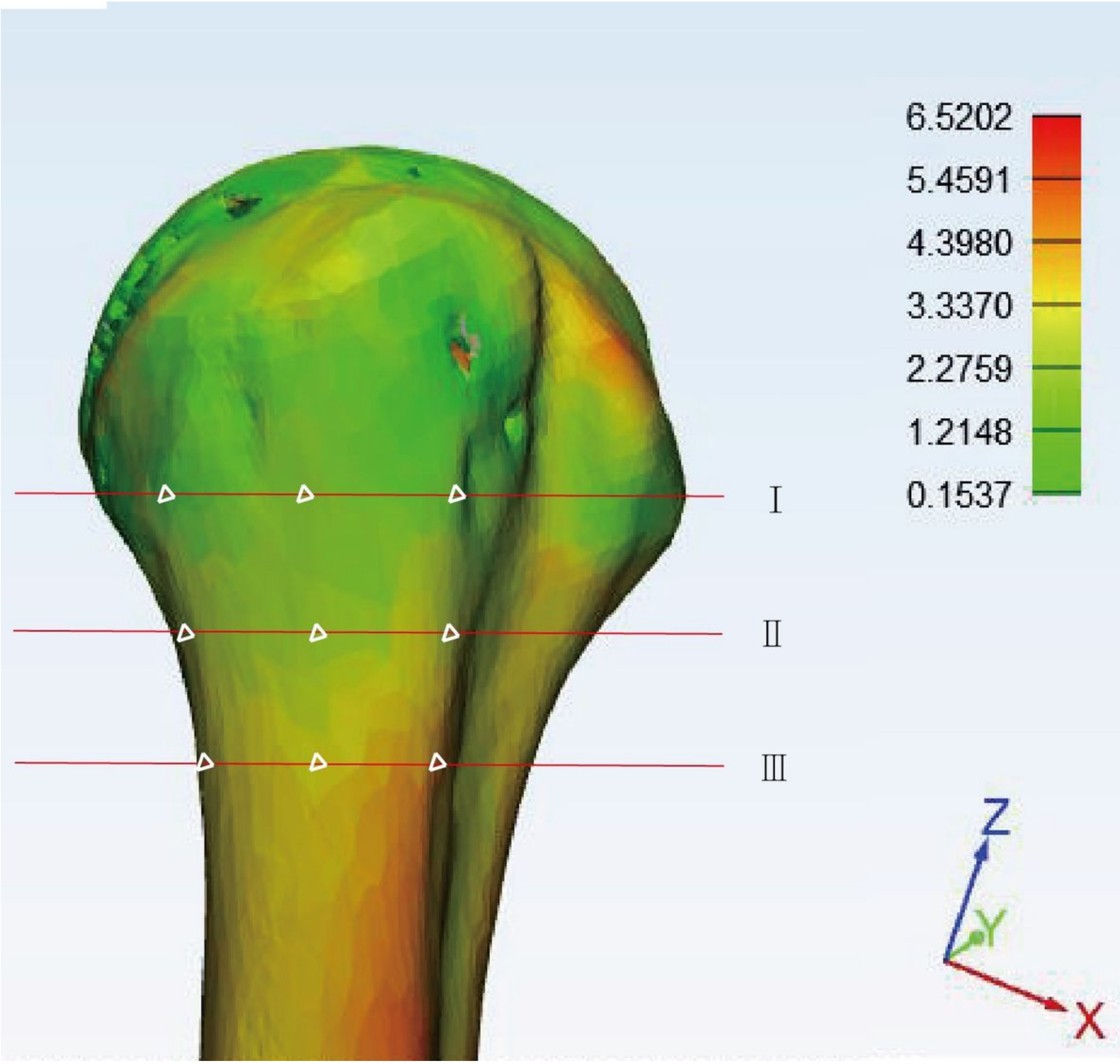

Figure 1

Cortical thickness measurement. Ⅰ. The line was located at the top of the lesser tuberosity to measure the cortical thickness of the RT. Ⅱ. The line located at the base of the lesser tuberosity was chosen as the plane to measure the cortical thickness of the surgical neck region. III. The line that was parallel and had the same distance from the above line to the first line was chosen as the plane to measure the cortical thickness of the diaphysis. Three points were selected adjacent to the bicipital groove (anterolateral), middle of the greater tuberosity and posterolateral point.

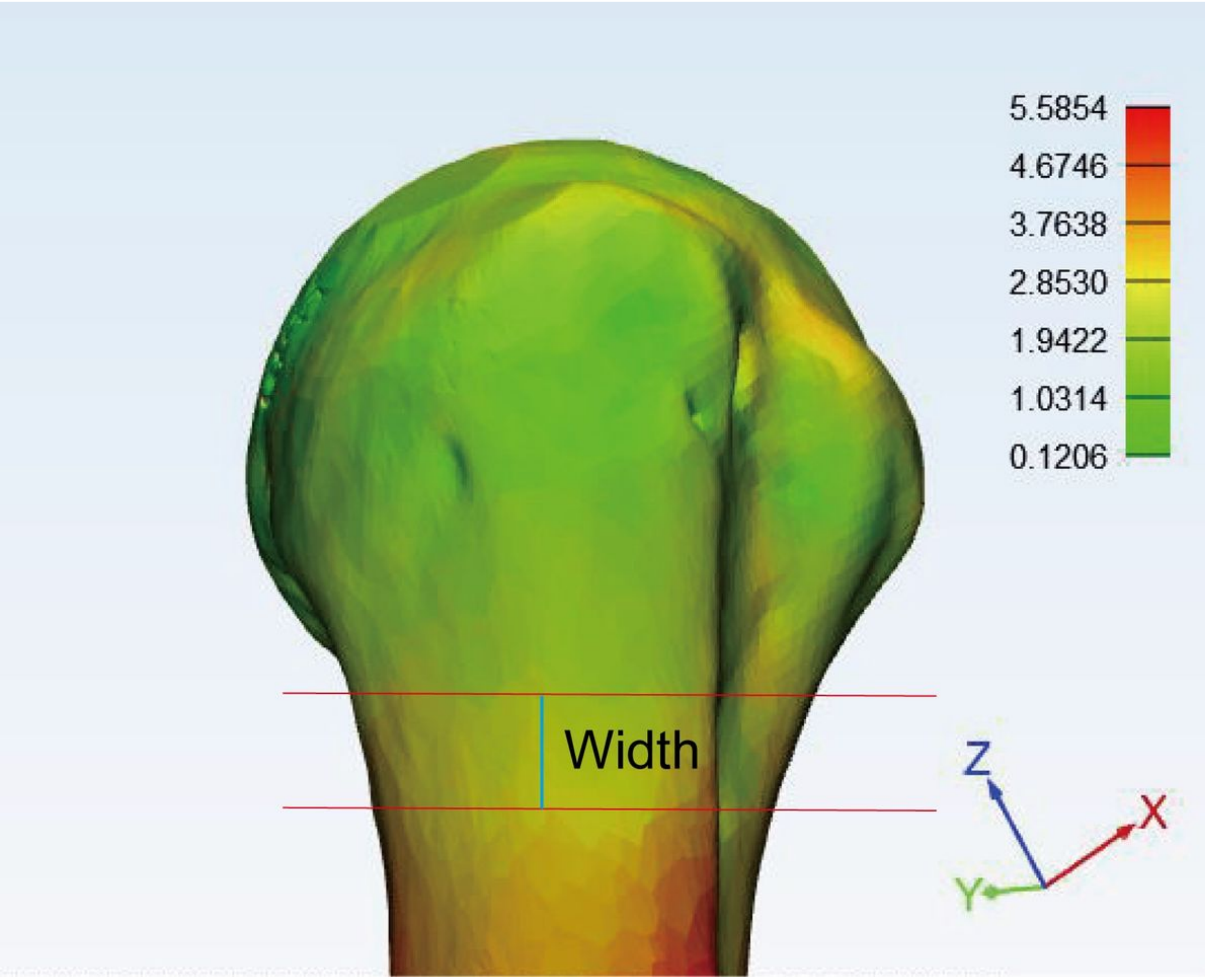

Figure 2

Measurement method of the surgical neck region width. The rectangular region was considered the valid width.

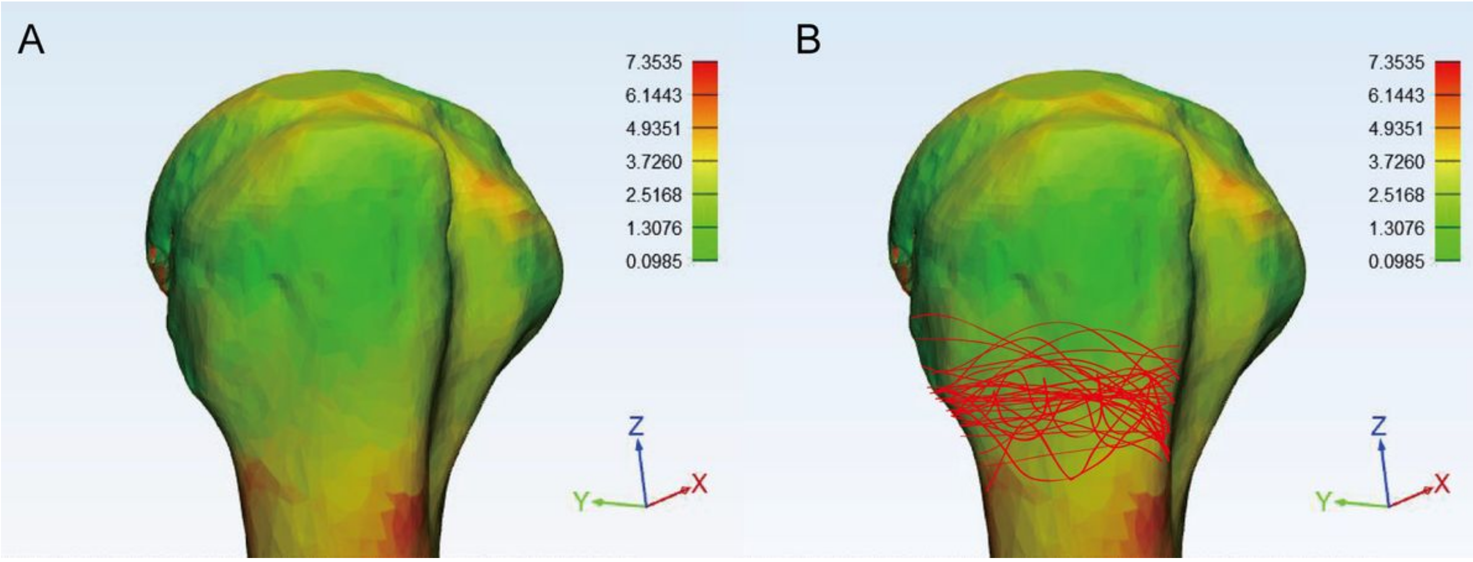

Figure 3

Fracture line distribution in a 23-year-old male patient. A. The cortical thickness template in a male patient. B. The distribution of surgical neck fractures in this male patient.

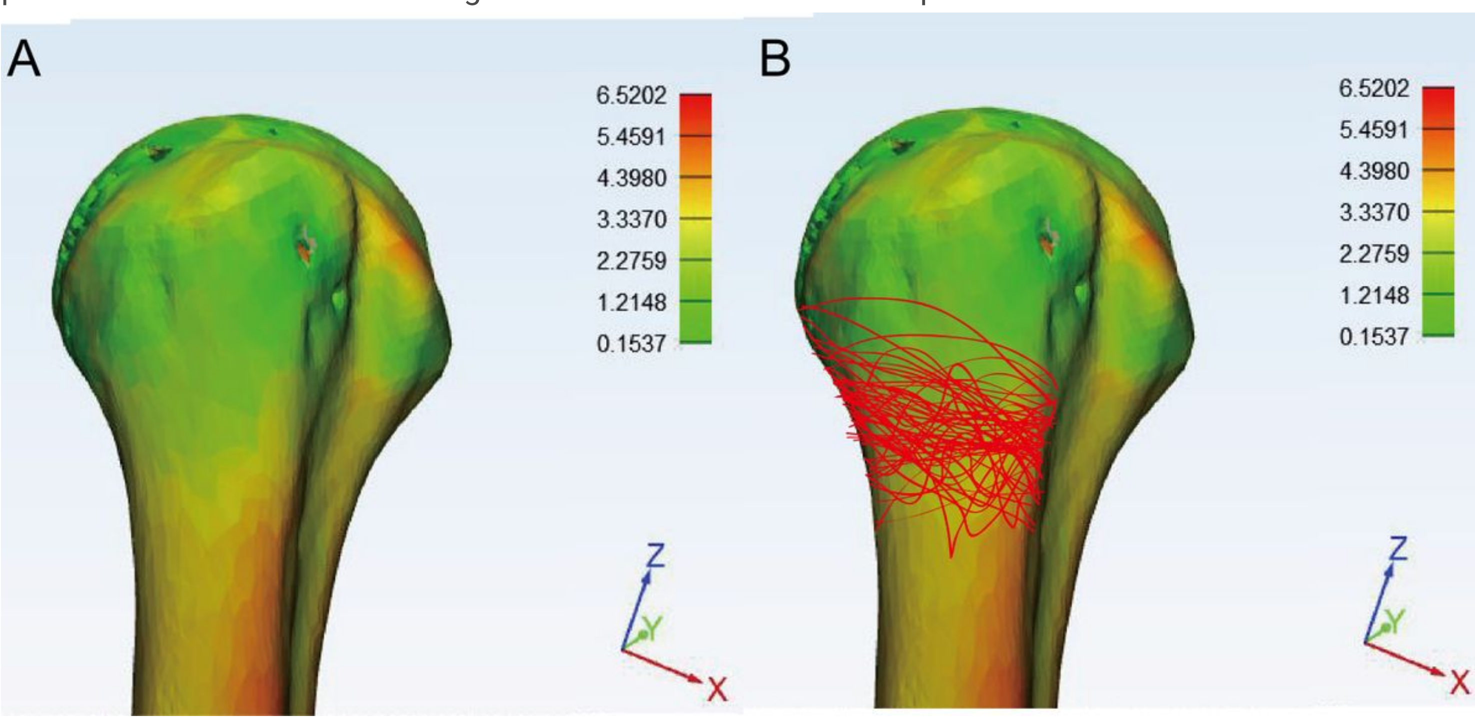

Figure 4

Fracture line distribution in 29-year-old female patients. A. The cortical thickness template in a female patient. B. The distribution of surgical neck fractures in this female patient.

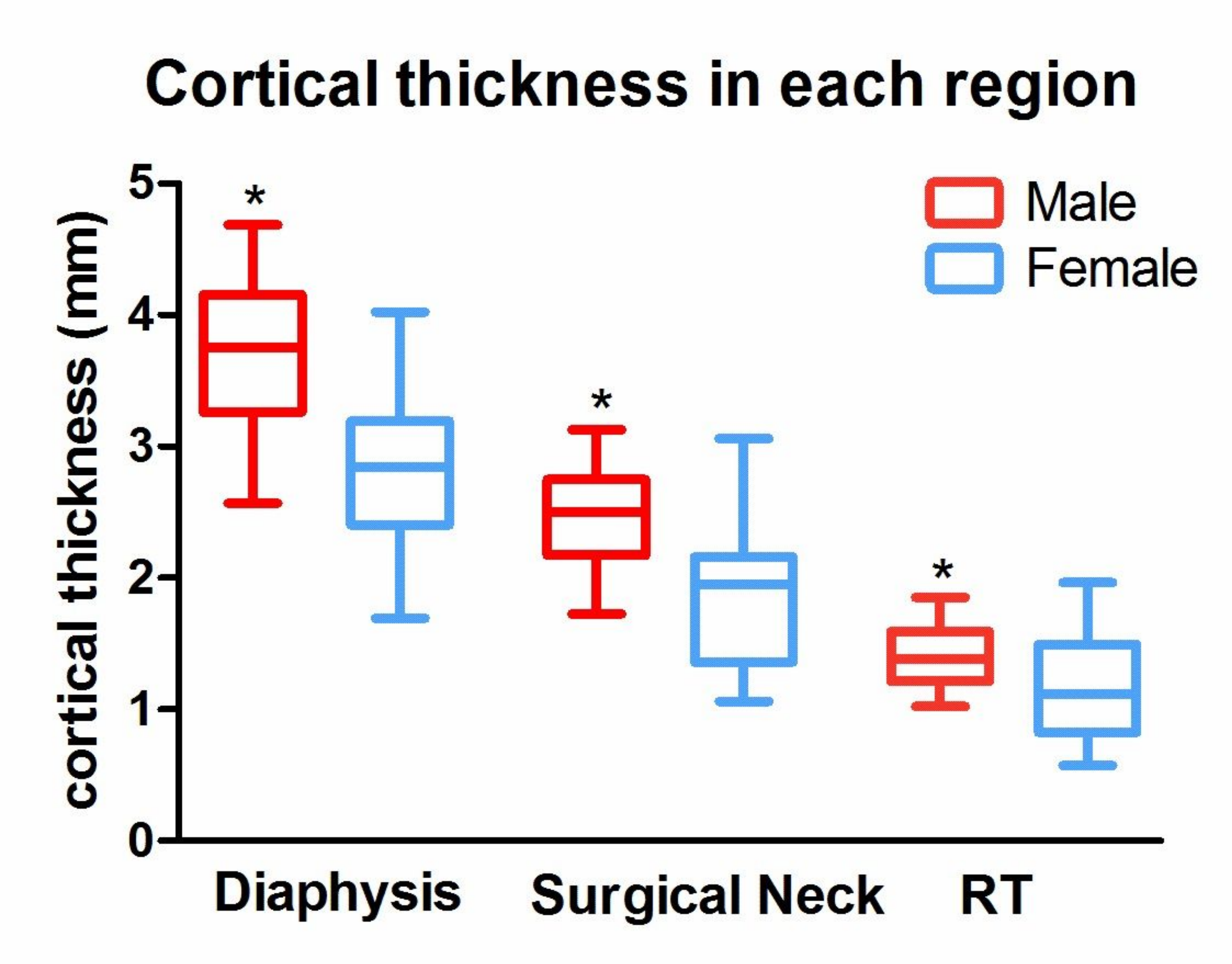

Figure 5

Comparison of cortical thickness in RT, surgical neck and diaphysis regions. * indicates a significant difference between males and females.

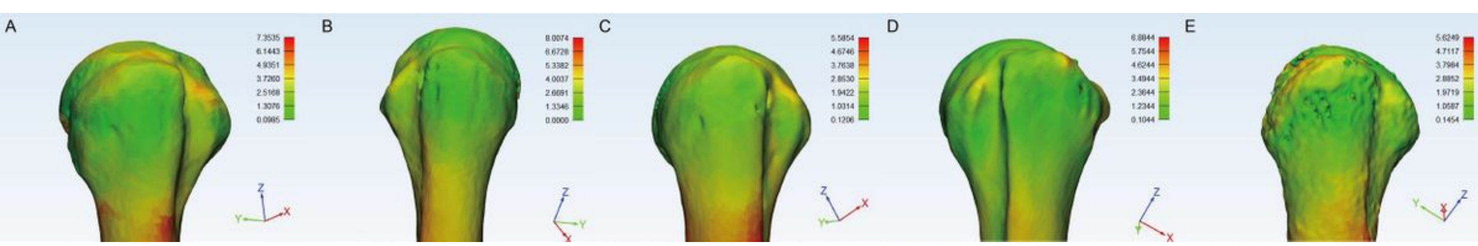

Figure 6

Different cortical thicknesses in the surgical neck region remained obvious as age increased. A surgical neck region in a 23-year-old patient. B. Surgical neck region in a 28-year-old patient. C. Surgical neck

region in a 34-year-old patient. D. Surgical neck region in a 53-year-old patient. E. Surgical neck region in a 70-year-old patient.