Although a variety of mechanisms can result in fractures of proximal humerus, most commonly the patient suffers a fall to the side, with the arm by his or her side, or onto the outstretched arm [1]. The resulting fracture patterns are largely dictated by the microstructure of the bone whereas conversely, the soft tissues including the periosteum often determine the degree of displacement and fracture stability. It is possible to correlate between the cortical thickness of the proximal humeral diaphysis measured on conventional radiographs and the bone mineral density of clinically important locations in the proximal humerus [2]. It has also been demonstrated by peripheral-quantitative-computed-tomography, that volumetric bone mineral density (vBMD) of the upper head shows significantly higher trabecular and cortical vBMD than the lower humeral head [3]. Meanwhile, the mean trabecular vBMD of the articular surface is significantly higher and the cortical vBMD is significantly lower than that of the tuberosities. The conclusion is that there must be zones of safety in fracture fixation. These findings may explain the observation of finding fracture patterns involving the tuberosities. This concept is echoed in the findings of Yamada et al. who found differences in humeral head bone tissue distribution depending on age, gender and location [4]. Changes in microstructure associated with age and osteoporosis readily accounts for the extension of a Hill-Sachs lesion to a greater tuberosity fracture as a consequence of dislocation (fig. 1).

The controversy of classification of proximal humeral fractures lies with the complex multi-fragmentary fractures without dislocation. At first sight these seem to form a diverse group with apparently different fracture patterns. However, observation suggests that these are angulatory deformities with secondary fracture lines dictated by weakness of the microstructure and the constraints of the soft tissues. Although Neer's modification of Codman's classification system for fractures of the proximal humerus [5, 7], wisely accom-
modates soft tissue disruption by quantifying fragment displacement; the comparison of tuberosities with the classic "parts" may falsely suggest disruption of the blood supply to the humeral head [8-10] and retraction of the rotator cuff insertions. Our studies suggest that the loss of viability of the humeral head may be over-estimated and that the tuberosities are often spatially orientated with minimal deflection other than by the primary distortion of the head with respect to the shaft.

![Fig. 1: MRI of Hill Sachs defect with progression to fracture through the greater tuberosity.](image)

The Neer system seems simple and well defined, but when applied to radiographs rather than the fracture pattern seen at surgery, it fails to give an acceptable interobserver error or to correlate with prognosis [11-21]. The lack of interobserver error can easily be explained by the use of two-dimensional X-ray analysis of a complicated three-dimensional body, as any change in rotation or loss of image quality will affect the interpretation. The difficulties of analysing these fracture has led to the increased use of three-dimensional CT reconstruction; however, even plain films read together with standard axial CT fail to produce a reliable classification system [11]. One study showed no significant differences between interobserver agreement whether 2 or 3 views or CT scans were examined and the authors concluded that to enhance consistency in understanding these fractures, imaging must be enhanced [22]. Of greater concern to us was the inability to predict outcome, plan management or most importantly understand mechanism of injury [21]. Interestingly, Neer based his classification on X-rays of fractures made before treatment and correlated image patterns with operative findings. Tamai et al recorded the gross anatomy of 22 patients with 3-part and 4-part fractures and compared these with pre-operative radiographs in a blind manner [23]. They found, soft tissue attachments to the head were closely related to the articular surface orientation on radiographs rather than the number of segments or AO classification and defined two distinct categories of injury not corresponding to the Neer or AO classification.

Hertel introduced a classification system based on a binary decision process regarding five basic fracture planes and from this a combination of fracture patterns can be represented using LEGOR blocks. Additional descriptors such as the length of the medial metaphyseal extension and the integrity of the medial hinge were the most relevant predictors of humeral head ischaemia, which provided to the classification system with strong prognostic decisional elements [24]. Similar to Codman's classification involving the four key elements, the greater tuberosity, the lesser tuberosity, the articular head and the humeral shaft, Hertel's paper illustrates their arrangement in various permutations.
Edelson et al. recently challenged the concept of a mechanism of injury in which the tuberosity is "pulled apart" [25]. This study used 73 fractures of the humeral head culled from three thousand two hundred humeri found in eight museum collections; together with clinical examples from 84 patients with proximal humeral fractures seen by the authors over a 3 year period. CT 3-D Reconstructions were performed on all patients. This allowed three-dimensional understanding of the fracture, "which can be obtained by holding museum specimens in hand and examining them from multiple directions". For the clinical cases they added, "The possibility of looking at fractures in this way is now available, in vivo, using CT 3-D reconstruction techniques".

We approach the problem in a similar way with the creation of 3D reconstructions (fig. 2a, b, c) via the use of stereo lithography STL (computer assisted design) software (MIMICS). The STL file produced is widely used for rapid prototyping and computer-aided manufacturing. STL files describe the surface geometry of a three dimensional object by describing a raw surface by and vertices using a three-dimensional Cartesian coordinate system. This allows the subsequent creation of physical 3D models from profiled data or 'masks', using rapid prototyping technique (fig. 3 a,b,c). Twenty-five consecutive cases with complex proximal humeral fractures were CT scanned. Fracture-dislocations were excluded. In keeping with other studies, independent assessment of each model by consultant, fellowship trained surgeon and surgical SHO showed poor agreement with either the Neer or AO classification [26]. In many cases one or more observers were unable to classify many of the fracture patterns seen.

**Fig. 2: 3D masks in MIMICS**
The use of physical models allowed a careful analysis of these complex three-dimensional shapes (fig. 4). The major observation was the principle displacement is between the head and the shaft with the greater tuberosity remaining relatively static in space with respect to the scapula and acromial arch. The appearance suggested that force was applied in either valgus or varus with the humeral head held against the glenoid. It appears that the glenoid, which preserves its hard-packed bone even into late old age, is the “anvil” on which the head breaks [25]. In the cases of varus angulation, the fracture was often associated with buckling or disruption on the medial hinge (fig. 5). Buckling in this region was also seen with posterior angulation and torsion of the major fracture fragments.
The majority of cases demonstrated backward tilting of the head on the shaft similar to two part surgical neck fractures. A very common pattern seen in multi-fragment fractures leaves the lesser tuberosity attached to the posteriorly tilted head fragment, often with a undisplaced fracture line. Another potentially important pattern was the “Shield” type [25]; involving all, or a majority, of the lesser tuberosity, the intact bicipital groove and the greater tuberosity (fig. 6). The bicipital groove in these injuries does not constitute a plane of cleavage between tuberosity fragments, as conceived in the Neer “4-Part” system, but rather forms a firm cortical backbone which holds the tuberosities, or portions of them, together. In keeping with Edelson et al we found the “shield fracture” is most easily understood as a worsening and a progression of a “3 Part” injury pattern as the head segment continues to be driven down and back. The cartilaginous head is sheared off from the “Shield” by the anvil edge of the glenoid and tilts backwards, as in the simpler fracture forms, into varus or into true valgus.

The existence of a “4-Part” injury involving both tuberosities as discrete, separate entities seems quite rare. What is conceived as the classic Neer “4-Part” pattern is, in fact, a variety of “Shield fracture”. It is composed of a relatively small segment of greater tuberosity (GT) attached to the hard bone of the biceps groove and via the groove to the lesser tuberosity (LT). This concept is noted by
Hertel, whose binary classification includes the H-GLS (head fragment separate from GT, LT and shaft unit) and HS-GL (GT and LT fragment united and separate from the humeral head-shaft unit) [24]. The concept of the GT and LT remaining as a distinct entity was noted by Sallay et al. whose use of 3D CT scans demonstrated not only that this facility did not improve poor agreement between observers but showed in 11 out of 12 cases, a fracture fragment composed of the intertubercular groove with varying portions of the lesser and greater tuberosities either freestanding or attached to the shaft or articular surface. The authors found difficulty in classifying this according to the Neer classification [27]. Additionally, Tamai et al found 6 out of 22 intra-operative cases with similar findings although linear fractures were found in the intertubercular region [23]. This group also found a fracture pattern consisting of the LT attached to the shaft with separate head and GT fragments, which have three parts as classified on radiological and surgical assessment, but differed from what Neer described as a 3-part fracture.

In one of its most common and destructive expressions, the “Fracture Shield” pattern may account for what Neer characterised as a “head-split” fracture [25]. In this, as in other types of Shield injuries, the majority of the head is detached and driven backwards by the thrust of the glenoid. But, in this type, a part of the cartilaginous head is left attached to the fracture “Shield” element. Most greater tuberosity fractures are combined injuries associated with either “3 Part” or “Fracture Shield” patterns. In general, the hard bone of the superior glenoid engages and crushes the greater tuberosity slightly behind the supraspi- natus facet. Avascular necrosis occurs most commonly in “Shattered Shield”, in other severely displaced “Shield Variants”, or in severe Fracture Dislocations in which the cartilaginous head is detached completely [25].

The models were further analysed by the insertion of K wires to create lines of reference to allow optical goniometry. Measurements of articular head fragment allowed the angle of inclination, angle of torsion and degree of posterior angulation were obtained. In our series the angle of inclination measured 92 to 185 degrees (mean = 140); Torsion 9-115 degrees (mean = 43) and Posterior angulation 0-88 degrees (mean = 29). The study demonstrated that the fractures followed a far more similar pattern than originally considered with a continuous graduation of head shaft angulation in multiple defined planes. In keeping with any spectrum, the appearance can only be scientifically described by numerical data rather than true groups. Understanding of these angulations is essential for the mechanism of injury and to provide a logical method of reduction.

We have extended our initial series in excess of 60 fractures and we propose a digital method of measuring angulation of fracture segments by the application of bespoke software, which calculates the morphology of the fractured proximal humerus by fitting ellipses to the axial sections to obtain axis which when applied to lines of reference allow the digitally demonstration of angles of inclination, torsion and posterior angulation (fig. 7 a, b). There has been successful application of digital 3-dimensional analysis of the proximal humerus and to the design of proximal humeral prostheses [28].
extremity injuries. Proximal humeral fractures may also occur via other mechanisms of injury such as direct impact against the ground or against some other hard object. Nonetheless the glenoid remains the anvil against which the head is broken [25].

The greater understanding of these fractures encourages attempts at anatomical reduction and stable fixation. However, the enthusiasm must be supported by clinical outcome and the relative risk of avascular necrosis. For example, the incidence of avascular necrosis is variable, probably as a consequence of inaccurate classification, rather than reflecting genuine differences. It is agreed the incidence may be increased by surgical intervention, exemplified by the low incidence in neglected cases. It is undoubtedly unwise to attempt reconstruction of a proximal humeral fracture unless the surgeon has a clear understanding of the injury in 3 dimensions. It is interesting to note that recent large scale studies have suggested that procedures done under the direction of classification systems based on 2 dimensions alone are no better than non surgical treatment [30-35].

3D spatial appreciation of fracture fragments is essential in improving the understanding of fracture morphology and attributing any related classification systems. We feel, the addition of angulatory data not only improves the surgeons understanding and better prepares him in the planning phase but also represents a defined pattern of injuries for which outcomes can be monitored and related. The ability to define cortical thinning enhances the surgeons’ awareness of ‘safe fixation zones’. 
Acknowledgements

The authors wish to express they thanks to Shirely Fetherston, Imperial College Healthcare NHS Trust for all her help with this study.

REFERENCES


