Effects of proximal humeral fracture morphology on glenohumeral range of motion

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Abstract

The morphology of proximal humerus fractures varies greatly, ranging from non-displaced 2-part fractures to 4-part fractures with inclined articular surfaces and displaced tuberosities. Existing classification systems attempt to formalise these features and relate them to clinical results. The repeatability of these classification systems has been shown to be poor, giving rise to the question whether a more objective measure entails improved predictability of outcome.

Using a system that simulates bone-determined range of motion of spheroidal joints such as the shoulder joint we categorically analysed a series of 79 proximal humerus fractures. Morphological properties of the proximal humerus fractures were related to simulated bone-determined range of motion.

The interobserver variability of range of motion assessment using our system showed excellent agreement (0.798). Maximal glenohumeral abduction and forward flexion of intra-articular fractures were $34.3 \pm 6.6$ SE and $60.7 \pm 12.4$ SE degrees. For fractures with a displaced tuberculum major they were $75.0 \pm 5.9$ SE and $118.2 \pm 4.9$ SE degrees, for fractures where both tuberosities had been displaced they were $60.0 \pm 10.9$ SE and $69.6 \pm 13.4$ SE degrees. For non-intra articular fractures without displaced tuberosities they were $89.3 \pm 3.3$ SE and $122.6 \pm 3.4$ SE degrees. The head inclination angle was positively correlated with maximum abduction ($0.362$, $p = 0.014$). Offset was negatively correlated with maximum abduction, but not statistically significant ($0.834$, $p = 0.087$).

We conclude that intra-articular fractures generally have the worst prognosis with regards to bone-determined range of motion. Fractures with displaced tuberosities show more motion limitations for abduction than for forward flexion. A reduced head inclination angle is a strong predictor of limited bone-determined range of motion for all types of proximal humerus fractures. No correlations were found between the maximum forward flexion range and the measured morphological parameters, indicating that it is difficult to predict range of motion based on morphological parameters only and that extensive range of motion simulation is required to predict outcome.
5.1 Introduction

Proximal humerus fractures (PHFs) often occur in the elderly population as a result of falling from standing height and are often osteoporosis related. The treatment options include conservative treatment and surgical intervention, the latter ranging from percutaneous wire fixation or open reduction and internal fixation to hemi-arthroplasty. The treatment decision is based on patient age, assessment of image modalities such as radiographs and computed tomography (CT), as well as the application of fracture classification systems found in the literature. However, the classification systems have been much disputed for their reproducibility and effectiveness in predicting outcome.

The first PHF classification system was published by Codman, who differentiated between the humeral head, the humeral shaft and the tuberosities (Codman, 1934). An extension of Codman’s classification system, and the most frequently used classification system, is the classification system by Neer (Neer, 1970). The Neer classification system differentiates between 2-, 3- and 4-part fractures as well as the dislocation of fragments. In recent years the notion has occurred that second order effects such as vascularity must be taken into account when assessing PHFs, leading to the classification system proposed by the Arbeitsgemeinschaft für Osteosynthesefragen (AO) (Müller et al., 1994). Recently, Hertel developed a binary fracture description based on fracture planes rather than the number of fragments and found correlations between the classification and restriction of blood supply (Hertel et al., 2004).

In the literature, the intra-observer repeatability and interobserver reliability for Neer classification has been proven to be fair or poor, with Kappa values ranging between 0.40 to 0.60 (Bernstein et al., 1996, Kristiansen et al., 1988, Sidor et al., 1993, Siebenrock and Gerber, 1993). Simplification of the classification system subdividing the fractures into fewer categories did not significantly improve these values (Sidor et al., 1993). As demonstrated by Majed et al., removing imaging subjectivity in the production of prototype models of the fracture did not improve the reliability for Neer and AO PHF classification systems (Majed et al., 2011a). This persisting subjectivity of the PHF classification systems in combination with the severe implications of treatment decisions encouraged us to assess the possibilities of a computerised assessment rather than a subjective classification.

There are many aspects involved in the evaluation process that precede the treatment decision of a PHF. However, the morphology of the glenohumeral joint and loss of smooth articular congruency may be a significant cause of loss of motion. Indeed, fracture fragment deflection has been argued to cause vascular insult (Müller et al., 1994). Displacement is affected by tendon attachment points (Neer, 1970), while passive range of motion (ROM) is affected by impingement of rigid structures and displacement of the articular surface of the humeral head (Edelson et al., 2004).
this article we assess impingement and interrupted articulation using a computerised simulation model.

The main objective of this study is to define the relationship between three shape parameters of PHFs and the inherent bone-determined ROM in a dynamic simulation model. In addition we look at the simulated bone-determined ROM when a categorical approach is taken. The morphological properties of 79 cases of PHFs were determined using CT scans. The bone-determined ROM was independently estimated by two observers using a software package designed for this purpose. With this study we demonstrate that bone-determined ROM simulation of fractures may be a valuable supportive instrument in the decision-making process involved in the treatment of these fractures.

### 5.2 Methods

#### 5.2.1 Data description

For this study a collection of 100 anonymised post-trauma CT scans of the shoulder area of PHF-patients was utilised. Exclusion criteria were poor image quality and the presence of abnormalities such as recurrent fractures or prosthetic materials. After application of the exclusion criteria 79 datasets remained. The remaining CT scans were segmented and converted to surface models using Mimics (Materialise NV, Leuven, Belgium). For each dataset a scapula model and humerus model were obtained.

#### 5.2.2 Shape classification

To investigate the implications of different fracture patterns we have categorised our data into four groups. The groups are illustrated by Figure 5.1 and had the following characteristics: 1) Intra-articular fractures, 2) fractures with a displaced tuberculum major, 3) fractures with a displaced tuberculum minor and major, also known as a 'shield', and 4) all other fractures that do not belong to the former groups and do not satisfy the exclusion criteria. A fragment was considered displaced when a step was present on the surface. It was hypothesised that each of the groups would have ROM limitations characteristic of the distinctive morphological properties.

Head inclination, sagittal head angulation and offset were measured in accordance with a process described by Majed et al. (Majed et al., 2011b). Each model underwent a process of endosteal and periosteal morphological assessment (see Figure 5.2). Proximal ellipse fitting defines a distal major and minor axis whilst an intramedullary axis is determined. The centre of the humeral head is determined after sphere fitting to the articular surface, whilst an ellipse is fitted to the articular
5.2.3 Range of motion simulation

ROM simulation was performed using a previously described system with minor modifications (Clinical Graphics, Den Haag, The Netherlands). The system was originally developed for pre-operative planning of shoulder arthroplasty (Krekel et al., 2006). In a cadaveric study we demonstrated that the error margin of the predicted angles of impingement lies within a range of 5 degrees (Krekel et al., 2009). For this study we have adapted the system to support geometry of PHF cases. Adaptations involved skipping the prosthesis placement functionality and implementing minor modifications of the bio-mechanical model to accommodate for the non-conformity of the glenoid fossa and humeral head, as described below.

The simulation routine is initiated by importing 3-D models of the scapula and humerus. Subsequently, the system calculates the position of well-known landmarks. Planes are moved through the object to find the most extreme points on the models. The centre of rotation of the glenoid is determined by applying a Hough-transform to the surface models. Landmarks can also be selected manually. For this study, landmarks were calculated automatically and verified by an orthopaedic surgeon.

Figure 5.1: The four categories we adopted for our data. 1) Intra-articular fractures, 2) fractures with a displaced tuberculum major, 3) fractures with a displaced tuberculum minor and major and 4) all other fractures that do not belong to the former groups and do not satisfy the exclusion criteria.
Figure 5.2: Measured morphological parameters. The centre of the head is determined by sphere fitting to the articular surface and defines the offset with respect to the intramedullary axis (a). Head inclination is determined by the intramedullary axis of the humeral shaft and the long axis of an ellipse fitted to the articular margin (b). Sagittal head angulation is determined by the intramedullary axis of the humeral shaft and the short axis of an ellipse fitted to the articular margin (c).

To dynamically simulate bone-determined ROM, we have implemented a biomechanical model of the gleno-humeral joint. A generally accepted hypothesis is that the gleno-humeral joint can be approximated by a ball-joint (Van der Glass et al., 2002, Meskers et al., 1998). When the humeral head is fractured, joint articulation may be affected, thereby jeopardising this hypothesis. Displacements of the articular surface with respect to the glenoid are taken into account by considering motion of the humerus invalid when the articular surface loses contact with the glenoid fossa.

Joint stabilising forces normally provided by the rotator cuff during arm motion are simulated by applying a translation of the humerus towards the glenoid surface. When the humeral head reaches the glenoid, further translation is halted. This enforces contact between the glenoid fossa and the humeral head.
Figure 5.3: The ROM simulator. A kinematic model is applied to surface models of the scapula and humerus (a). When impingement is detected by a collision detection algorithm the bone is coloured red (b). Interrupted articulation of the joint is not detected automatically and therefore two observers analysed the series of fractures (c).

We used the scapula coordinate system as described in the recommendations of the International Society of Biomechanics (Wu et al., 2005). In this chapter, clinical terms are used to describe motion. Forward flexion refers to elevation parallel to the sagittal plane. Abduction refers to elevation in the coronal plane and internal rotation refers to axial rotation along the humeral shaft.

After initialisation, the posture of the humerus can be manually adjusted. While the posture is adjusted, a collision detection algorithm evaluates whether geometric objects are intersecting (Terdiman, 2001). If impingement is detected, the humerus is coloured red, alerting the user that the given posture is invalid (see Figure 5.3). Interrupted articulation of the humeral head on the glenoid is visible in the simulations but not automatically detected. For this reason two observers operated the system manually.

To quantify the ROM of the individual PHF cases, the maximum range of forward flexion and abduction was determined. Because the scanned arm position and orientation was not controlled at the time of data acquisition, the neutral orientations of the humeri were indeterminable. To account for this, we performed the ROM measurements for different degrees of axial rotation. Maximum abduction and maximum elevation were measured in 40 degrees and 20 degrees of internal rotation, in the neutral (scanned) position, and in 20, 40, 60 and 70 degrees of external rotation. Generally, when lying down in the CT scanner, patients will have their arm moderately
internally rotated to minimise pain. Therefore we chose to evaluate a larger range of external rotation than internal rotation. In total an axial rotation range of 110 degrees was analysed. The findings of both observers were compared to evaluate the interobserver variability. To obtain the final values for maximum forward flexion and abduction of each of the fractures the measurements of the observers were averaged. The results were statistically compared to the shape parameters of the models.

5.2.4 Statistical Analysis

For statistical analysis the SPSS software package was used (SPSS Inc., version 17.0, Chicago, Illinois). The interobserver variability of our measurements was assessed using the Pearson product-moment correlation coefficient (PMCC). For interpretation, the criteria formulated by Cicchetti and Sparrow were used: 0.00 to 0.39, poor; 0.40 to 0.59, fair; 0.60 to 0.74, good; or 0.75 to 1.00, excellent (Cicchetti and Sparrow, 1981). General linear models were used to determine correlation between morphological parameters and ROM. Statistical results were considered statistically significant when \( p < 0.05 \).

5.3 Results

We studied the standard error of the mean of the ROM measurements (see Figure 5.4). The ROM measurements indicate that intra-articular fractures have the smallest range for abduction and forward flexion (34.3±6.6 SE and 60.7±12.4 SE), followed by shield-type fractures (60.0±10.9 SE and 69.6±13.4 SE). Fractures with just a displaced tuberculum major show limitations for abduction, but not for forward flexion (75.0±5.9 SE and 118.2±4.9 SE). This can be explained by the displaced tuberosity, colliding with the acromial arch. Finally, non-intra-articular fractures that do not have displaced tuberosities have ROM that is comparable to that of healthy subjects (89.3±3.3 SE and 122.6±3.4 SE versus 102.3±2.8 SE and 96.2±3.8 SE).

No correlation was found for head inclination versus maximum forward flexion for any of the groups. This also holds for sagittal head angulation versus maximum forward flexion and offset versus maximum forward flexion. However, for all groups head inclination correlated with the maximal abduction range (see Figure 5.5). With multiple linear regression it was determined that the slope of each of the categories was similar (\( p = 0.941 \)). The slope of the head inclination versus maximal abduction was approximately 0.362, meaning that for every degree of head inclination the bone-determined abduction range increases with 0.362 degrees. The correlation coefficient was 0.482, indicating a moderate correlation. This result was statistically significant.
Figure 5.4: Maximal angles relative to the scapula. Displayed are the mean±SE. Shield type fractures have a displaced tuberculum major and minor. Other type fractures do not belong to the other three categories. For the reference of the ROM of healthy subjects (marked *) we used the information from the study by Magermans et al. (Magermans et al., 2005). In contrast to the four preceding categories these data consist of actual recorded ROM in 24 healthy subjects.

\( p = 0.014 \). The intercepts cover a range of 56.5 degrees, showing clear distinctions between the groups. The low intercept of intra-articular fractures indicates that these fractures have the worst prognosis to start with. Regardless these fractures show a similar improvement with increased head inclination angle in comparison to other groups.

Maximum abduction did not correlate with sagittal head angulation (-0.070, \( p = 0.303 \)). It did correlate negatively with offset with a slope of -0.834, but this correlation was not statistically significant (\( p = 0.087 \), see Figure 5.6).

The interobserver variability of the ROM measurements was 0.798, showing ex-
Figure 5.5: Maximal abduction versus the measured head inclination angle. The linear regression lines of all groups are increasing with respect to the head inclination angle. This indicates that a reduced head inclination angle is a strong predictor of limited ROM. This figure also shows that intra-articular fractures generally have a lower abduction range than other types.

cellent agreement.

5.4 Discussion

In this chapter we described a ROM simulation system used to quantify the bone-determined ROM of 79 cases of PHFs and related the results to fracture morphology. From this study it can be concluded that intra-articular fractures generally have the worst prognosis with regards to bone-determined ROM. During forward flexion but even more so during abduction the articulation of the glenohumeral joint is jeopar-
dised, preventing further motion. Fractures with displaced tuberosities show more motion limitations for abduction than for forward flexion. However, when the tuberculum minor is still attached, forward flexion is generally not problematic with regards to impingement. Only when both the tuberculum major and the tuberculum minor displace the maximum bone-determined forward flexion range is reduced.

Interestingly none of the morphological measurements, other than the categorisation of our data, had a predictive value with regards to the maximum forward flexion range for any of the groups. This as opposed to the maximum abduction range where some correlations were found with morphological measurements. Conclusions that follow from the data are that reduced head inclination angle is a relatively strong predictor of a limited abduction range for all types of proximal humerus fractures. Sagittal head angulation was not correlated with the maximum abduction range. Finally, offset of the articular fragment with regards to the intra-medulary axis correlated with the maximum abduction range, but not statistically significant. With the

Figure 5.6: Maximal abduction versus the measured offset.
Figure 5.7: AP and lateral radiographs of the proximal humerus fracture also depicted in Figure 5.3. With these radiographs it is difficult to distinguish between the different fragments of the fracture and to predict their influence on the bone-determined ROM.

relatively low p-value of 0.087, we are cautiously optimistic about the results that could be achieved testing with a larger number of CT scans.

Interrupted articulation at the glenohumeral joint as a result of displaced fragments is difficult to detect using traditional radiographs. As an example we have included the AP and lateral radiographs of the fracture that was depicted in Figure 3 (see Figure 5.7). The displaced tuberculum minor causing interrupted articulation in subfigure 3 is not distinguishable at these radiographs. A CT-scan reveals the displaced tuberculum minor. The described ROM simulations of the fracture answer clinically relevant questions and add to the conclusiveness of the assessment.

There are limitations to this study. The humeral epicondyles were not included in the CT scans. Therefore we were unable to measure retroversion of the humeral head. Additionally, we were unable to measure the absolute axial rotation of the humerus. To account for this, we performed ROM measurements for a large range
of elevation planes and used the maximum value as an indicator of mobility. In our opinion, this is a justified metric because patient treatment decisions are based on achievable functional results. A large elevation angle, regardless of the exorotation of the humerus, can be considered a desirable result.

The ROM simulation system does not incorporate soft tissues in the simulations. This entails that the true ROM of the patient will be smaller than the conservative estimate as determined by the simulations. However, the simulator detects collisions of rigid structures and these will also limit the active ROM of patients. In future work we wish to relate the ROM simulations to function.

Zyto et al. demonstrated that conservative treatment of complex proximal humeral fractures is arguably favourable relative to Neer’s doctrine of surgical intervention (Zyto et al., 1995, Zyto et al., 1997, Zyto, 1998). Furthermore, Nanidis et al. have demonstrated that outcome and complication rates are similar when treating 3 and 4 part fractures conservatively and operatively (Nanidis et al., 2010). However, being able to predict at least bony functional ROM has not been possible or described in the literature. The results up to now seem to point out that the determination of functional movement using our algorithms could positively augment the decision-making process.

5.5 Conclusion

We hypothesised that computer assisted assessment of bone-determined ROM may be a valuable addition to fracture classification systems. To this extent a study on the effects of fracture morphology on the bone-determined ROM was conducted using a ROM simulator based on CT. The interobserver agreement of two observers using the ROM simulator was excellent. This indicates that, when compared to the interobserver agreement of existing classification systems, patient-specific ROM simulations may be a good alternative in the support of treatment decisions for PHF.

From this study we conclude that intra-articular fractures have the worst prognosis with regards to bone-determined ROM. Fractures with displaced tuberosities show more motion limitations for abduction than for forward flexion. It was shown that a reduced head inclination angle is a strong predictor of limited ROM for all types of proximal humerus fractures. The possible relation between offset and maximum abduction range was not statistically significant. Finally, the measured morphological parameters do not seem to have predictive value for the maximum forward flexion range.

Motion simulation results of the adopted categories are clustered. This suggests that, besides a measure to predict function, the system may also be used to support
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classification of PHFs. It seems likely that a combination of a classification system and dynamic patient-specific simulations will result in improved results with respect to outcome prediction. In future work this claim must be validated with a large prospective study that includes a 1-year follow-up and the assessment of function.