Simulation of bone-determined range of motion in proximal humeral fractures

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Abstract

Background: Predicting the outcome following fractures of the proximal humerus is an important consideration when effectively counselling patients and planning treatment. The purpose of the present study was to analyze different proximal humeral fracture configurations, using a computerized simulation model, aiming to predict the range of motion (ROM).

Methods: The computer tomography scans of 79 proximal humeral fractures were analyzed using a customized software system that simulated the range of movement at the glenohumeral joint. Four fracture patterns were investigated: (1) head split fractures; (2) greater tuberosity fractures; (3) lesser tuberosity fractures; and (4) combined tuberosity fractures.

Results: Intra-articular fractures had the smallest mean (SE) range of abduction and forward flexion [34.3° (6.6°) and 60.7° (12.4°)]. Isolated displaced greater tuberosity resulted in limited abduction but not forward flexion [75.0° (5.9°) and 118.2° (4.9°)]. Isolated lesser tuberosity fractures displayed a ROM comparable to that of healthy subjects [89.3° (3.3°) and 122.6° (3.4°) versus 102.3° (2.8°) and 96.2° (3.8°)]. The reduced head inclination angle was a relatively strong predictor of a limited range of abduction for all fracture types.

Conclusions: The present study describes a novel simulation system used to quantify the bone-determined ROM in proximal humeral fractures and may be a useful adjunct in the diagnostic armamentarium for proximal humeral fractures.

Keywords

biomechanical modelling, collision detection, functional movement, prediction, proximal humeral fracture

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Introduction

Complex fractures of the proximal humerus may be treated surgically or conservatively. Operative intervention comprises both bone preserving (open reduction and internal fixation) and bone sacrificing procedures (prosthetic replacement). The results are varied irrespective of the specific strategy employed, with recent evidence suggesting that non-operative management can produce a similar outcome to surgery in the short term.^{1,2} The choice between these various options is often based on clinical assessment, analysis of plain radiographs/computer tomography (CT) images and the application of sometimes unreliable fracture classification systems.³

Predicting the outcome following fractures of the proximal humerus is an important consideration when effectively counselling patients and planning treatment, particularly because a loss of movement resulting in

disability is a common long-term sequela.^{4–6} Therefore, as an adjunct in the diagnostic armamentarium for these injuries, it would be useful to be able to predict loss of movement based on fracture configuration. Three- and four-part fractures would be particularly amenable to this because their outcome is similar

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with both operative and non-operative management, and therefore being able to predict a deficit in range of motion (ROM) based upon fracture configuration may influence the choice of treatment.^{7,8}

The lack of reliable prognostic tools, such as classifications systems, has dictated the need to explore the use of computerized assessment to determine whether the morphology of the proximal humerus and the subsequent loss of articular congruency that occurs during fracture can predict loss of motion. The purpose of the present study was to analyze the dynamic articulation of the fractured proximal humerus in the glenohumeral joint, using a computerized simulation model. In doing so, both the precise fracture pattern and bone morphological changes causing a loss of joint motion in difference planes could be defined.

Materials and methods

Study design

Prior to commencement of the present study, local ethical approval was obtained to evaluate anonymized clinical radiological data. In total, 106 consecutive proximal humeral fractures were available for analysis but four cases were excluded (three as a result of evidence of radiological union and one because of a corrupted dataset), leaving 102 cases eligible for study. Of these, 61 were right-sided and 41 were left-sided. Data on age were missing from ten scans, whereas information on sex was absent in 19 scans. Mean (range) age of the cohort was 58.1 years (range 21 years to 93 years) with an SD of 17.4 years. Exclusion criteria included poor image quality, physiologically impossible articulation and the presence of other anatomical abnormalities such as previous fracture. Physiologically impossible articulation was defined as when the articular surface had been disrupted to such an extent that motion would not be possible, or when the fracture extended into the metaphyseal region and prevented movement as a result of massive soft tissue disruption, pain and/or joint incongruity. Application of these exclusion criteria left 79 datasets eligible for analysis.

All CT scans were performed on either a Philips MX8000 or a Philips Brilliance 64 multi-scanner (Philips, Eindhoven, The Netherlands) with a slice thickness of 2.0 mm. The primary image plane was axial with a restricted field of view to the shoulder of 250 mm × 250 mm. Reformatting was undertaken using a Philips bone algorithm with a slice thickness of 1.0 mm. Scans were segmented and converted to surface models using Mimics, version 11.0, software (Materialise NV, Leuven, Belgium). For each dataset, scapula and humeral models were obtained.

Figure 1. Measurement of humeral head inclination. This was defined as the angle subtending a longitudinal line through the diaphysis (intramedullary axis) and a line perpendicular to the anatomical neck, in the coronal plane.

Fracture patterns

Our customized, validated three-dimensional (3D) CT scan-based computer algorithm allowing measurement of fracture geometry was used as described previously to allow the calculation of head inclination (Fig. 1), sagittal head inclination and posterior/medial offset (Fig. 2).^{9,10}

Four isolated fracture patterns were investigated (Fig. 3):

1. head split fractures;
2. greater tuberosity fractures;
3. shield type fractures (greater and less tuberosity fractures); and
4. lesser tuberosity fractures.

It was hypothesized that each of these groups would have a characteristic limitation in motion based on their distinct morphology.

Range of motion simulation

Range of motion simulation was performed using a customized software system that has been demonstrated to predict bone-determined ROM within an error margin of 5° .¹¹ This was originally developed for pre-operative planning of shoulder arthroplasty by the authors, with minor modifications subsequently made by the developer to omit prosthetic placement functionality and to accommodate for the nonconformity of the glenoid fossa and humeral head (PK, Clinical Graphics, Delft, Netherlands).¹² The scapula coordinate system was incorporated as recommended by the International Society of Biomechanics.¹³ In this, terms to describe motion include 'forward flexion' referring to elevation in the sagittal plane; 'abduction' referring to elevation in the coronal plane and 'internal rotation' referring to axial rotation along the humeral shaft.

Figure 2. Measurement of posterior/medial offset. Medial offset was defined as the distance between the centre of the humeral head and the intramedullary axis in the axial plane. Posterior offset was defined as the distance between the centre of the humeral head and the intra-medullary axis in the sagittal plane.

The simulation algorithm was initiated by importing 3D models of the scapula and humerus. The system subsequently calculated the position of constant landmarks. Objects were moved through the planes to identify the most peripheral points on the models. The centre of rotation of the glenoid was determined by applying a Hough Transform (a method to find shapes in an image) to the surface models. Landmarks could also be selected manually. For the present study, landmarks were calculated automatically and verified by two investigators. By adopting a ball-joint as a surrogate for the glenohumeral joint, a biomechanical model was created to calculate ROM.¹³ This technique is often limited by an alteration in joint congruency, as occurs with a head-split fracture, although this was accounted for by excluding cases of physiologically impossible articulations.

Displacement of the articular surface with respect to the glenoid was taken into consideration by invalidating humeral motion when the articular surface lost contact with the glenoid fossa. Translating the humerus towards the glenoid simulated joint stabilization forces normally provided by the rotator cuff during arm motion. When the humeral head reached the glenoid, further translation was prevented. This imposed contact between the glenoid fossa and the humeral head.

After initialization of the software, the posture of the humerus could still be manually adjusted, during which a collision detection algorithm evaluated whether geometric objects intersected. If collision was detected, the humerus was coloured red, alerting the user that the given posture was invalid (Fig. 4). Although this process could be automated, the two named observers (AM and PK) operated the system manually to ensure accuracy. To quantify ROM of the individual proximal humeral fracture cases, the maximum range

Figure 3. The four categories of fracture groups adopted for the cohort: (1) head split fractures; (2) greater tuberosity fractures; (3) shield fractures; and (4) lesser tuberosity fractures.

Figure 4. Range of motion simulator. The glenohumeral joint is approximated by a ball and socket joint (1). A collision detection algorithm is used to detect impingement and 'mis-articulation' of the joint (2 and 3).

of forward flexion and abduction was determined by measuring a continuous arc of movement before collision of the glenohumeral joint occurred. Static data was then recorded at various points of rotation to determine the maximum range of forward flexion and abduction. Neutral orientation of the humeri was indeterminable because arm position and orientation were not controlled at the time of data acquisition, and no proximal anatomical features were available to define humeral rotation. To account for this, ROM measurements for varying degrees of axial rotation as a deviation from the scanning position were performed.

Maximum abduction and elevation were measured in 40° and 20° of internal rotation respectively, in the neutral (scanned) position, and in 20°, 40°, 60° and 70° of external rotation. In the clinical setting, the majority of patients adopt a position of internal rotation when lying down in a CT scanner to minimize pain, and therefore a larger range of external rotation than internal rotation was evaluated. In total, an axial range of 110° was analyzed. To limit the data to a range that was relevant for activities of daily living, the maximum elevation values were capped at 130° and subsequently compared with values derived from 'healthy subjects'.¹⁴ Inter-observer variability was evaluated by comparing the findings of both assessors. To obtain the final values for maximum forward flexion and abduction of each of the fractures, the measurements of the two observers were averaged.

Statistical analysis

For statistical analysis, the SPSS, version 17.0, software package was used (SPSS Inc., Chicago, IL, USA). Inter-observer variability was assessed using the Pearson product-moment correlation coefficient. For interpretation, the criteria formulated by Cichetti and Sparrow were used: 0.00 to 0.39, poor;

Figure 5. Glenohumeral motion. Data are the mean (SE).

0.40 to 0.59, fair; 0.60 to 0.74, good; or 0.75 to 1.00, excellent.¹⁵ A general linear model performing univariate testing was applied to all four fracture categories separately and combined to determine the correlations of head inclination versus maximal forward flexion; sagittal head inclination versus maximum forward flexion; offset versus maximum forward flexion; and head inclination versus maximal abduction.

Results

Range of motion measurements indicated that intra-articular fractures (those involving the articular cartilage) had the smallest range for abduction and forward flexion [34.3° (6.6°) and 60.7° (12.4°)], followed by shield-type fractures [60.0° (10.9°) and 69.6° (13.4°)] (Fig. 5). Fractures confined to a displaced greater

Figure 6. Range of motion in abduction relative to head inclination. The linear regression lines of all groups are increasing with respect to the neck-shaft angle, indicating that a reduced neck-shaft angle is a strong predictor of limited range of movement. Additionally, intra-articular fractures generally have a lower range of movement.

tuberosity showed limitations in abduction but not for forward flexion [75.0° (5.9°) and 118.2° (4.9°)]. This can be explained by the displaced tuberosity impinging upon the lateral acromion. Finally, lesser tuberosity fractures had a ROM comparable to that of healthy subjects [89.3° (3.3°) and 122.6° (3.4°) versus 102.3° (2.8°) and 96.2° (3.8°)].

There was no correlation between coronal plane inclination, sagittal plane inclination, head offset ($r = -0.033$, $p = 0.242$) and maximum forward elevation ($r = -0.022$, $p = 0.312$). However, for all groups, head inclination correlated with the maximal abduction range (Fig. 6), with no significant intergroup differences ($p = 0.941$). The slope of the head inclination versus maximal abduction demonstrated moderate correlation ($r = 0.362$, $p = 0.014$). The intercepts cover a range of 56°, showing clear distinctions between the groups. The low intercept of intra-articular fractures indicates that these fractures have the worst prognosis to start with, but they still showed a similar increase in head inclination angle compared to other groups. Maximum abduction did not correlate with sagittal head angulation ($r = -0.070$, $p = 0.303$). However, humeral head

offset was associated with reduced abduction ($r = 0.4914$, $p = 0.087$). The inter-observer variability of the ROM measurements was 0.798, showing good to excellent agreement.

Discussion

The present study describes a novel simulation system used to quantify bone-determined ROM in proximal humeral fractures and relates the results to fracture morphology. Based on bone morphology and articulation, intra-articular fractures had the worst prognosis with regard to bone-determined ROM. This loss of range was characterized by a reduction in both forward flexion and abduction, with the latter being affected to a greater extent by the impinging fracture fragments. Fractures with displaced tuberosities also showed more restricted movement in abduction than for forward flexion, other than in displaced lesser tuberosity fractures where there was a greater reduction in forward flexion. Forward flexion was not restricted though when the lesser tuberosity remained attached.

Interestingly, none of the morphological parameters could predict the range of maximum forward flexion for any of the groups. This was in contrast to the maximum abduction range, for which all of the morphological parameters demonstrated correlation with the maximum bone-determined ROM. We speculate that this was a result of the rotation position of the humerus having a greater effect in forward flexion. This was not quantified in the present study and would therefore not generate a correlation coefficient. From the data, it is possible to conclude that reduced head inclination angle is a relatively strong predictor of a limited abduction range for all types of proximal humeral fractures. Sagittal head angulation was not correlated with the maximum abduction range. Finally, offset of the articular fragment with regard to the intramedullary axis showed a trend associated with the maximum abduction range, although this was not found to be statistically significant.

The limitations of the present study include the inability to measure absolute axial rotation of the humerus. Thus, the ROM measurements for a large range of planes were determined and the maximum values were used as indicators of capable motion. It was considered that this was a justified method of assessment because treatment decisions are often based on the potential for achievable functional results. For example, a large forward flexion/elevation angle, despite external rotation of the humerus, may still be considered a satisfactory functional outcome for some patients. Additionally, the simulation system does not consider the influence of the scapulothoracic joint or incorporate the integrity of the soft tissue envelope

into the analysis and may result in an overestimation of ROM. Future studies should correlate simulation-determined ROM with actual clinical function.

The treatment of complex fractures of the proximal humerus is contentious but recent evidence suggests that the functional outcome in the short-term is similar following conservative and surgical management.^{1,16} Decision-making can be challenging and, to date, there have been no biomechanical studies predicting ROM in different fracture configurations. The customized computer algorithm described in the present study allows the evaluation of functional movement and may be a useful tool when counselling patients and deciding upon specific treatments. Our results indicate that intra-articular fractures have the least favourable prognosis with regard to bone-determined ROM and that reduced head inclination angle is a strong predictor of a poor ROM irrespective of fracture type. Fractures with displaced tuberosities are subject to a greater limitation in abduction than forward flexion, although this is dependent upon which tuberosity is involved.

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Ethical Review and Patient Consent

Joint RNOH/IOMS National Research Ethics Committee approval was received. REC reference number: 07/H0724/40. Patient data was anonymised, hence patient consent was not sought, as per the local ethics committee approval.

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