Complex distal humerus trauma
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**Introduction**

The distal humerus has an intricate osseous anatomy.\(^1\) The distal end of the humerus is translated anteriorly with respect to the shaft. This anterior projection of the articular surfaces allows clearance of the coronoid process and arm flexor muscles in flexion.\(^2\) \(^3\) \(^4\)

The trochelea is spool-shaped with a central groove and is bound by two convex lips accommodating the trochlear notch of the ulna. The medial and lateral ridges of the trochelea add to the intrinsic stability of the articulation. The capitellum is a hemisphere on the anterior aspect of the lateral column distally, articulating with the radial head. Immediately above the articular surfaces, three concavities are present: anteriorly, the coronoid fossa which receives the coronoid process during flexion and the radial fossa for the radial head during flexion; and posteriorly the olecranon fossa which receives the olecranon process of the ulna during extension.\(^5\)

The compact portions of the distal humerus lie on either side of these fossae, forming two divergent columns, one ending on the medial epicondyle, the other on the lateral epicondyle, with the articular surface (the capitellum and trochelea supported in between.\(^2\)

The ulnohumeral articulation has a range of motion of on average 145 degrees actively and up to 160 degrees passively.\(^6\) The range of forearm rotation (pronation and supination) is approximately 175 degrees.\(^2\) One highly quoted study of 10 common functional tasks reported that the majority of these tasks could be performed with a range of ulnohumeral motion between 30 to 130 degrees of flexion.\(^6\)

A three-dimensional analysis regarding ten activities in daily life, has found a range of necessary ulnohumeral motion between 146 degrees of flexion to 36 degrees of extension.\(^7\) Another recent study concerning more contemporary tasks has found an ulnohumeral motion between 149 to 27 degrees on average.\(^8\)

**Evaluation of Distal Humerus Fractures**

The complex anatomy of the elbow, the small size of the fracture fragments, and the limited amount of subchondral bone which is often osteopenic, make treatment of distal humerus challenging. Furthermore there exists a subset of these fractures that represents particularly difficult patterns of skeletal and articular injury. Among these are low columnar fractures,\(^9\) \(^10\) fractures that feature articular disruption in more than 1 plane or multiple fragments,\(^11\) \(^12\) capitellum and trochelea fractures, and fractures associated with extensive soft tissue injury or contamination.

**Fracture Patterns**

Columnar Fractures:

The Comprehensive Classification of Fractures\(^13\) is a comprehensive system for fractures of the long bones. According to this system, distal humerus fractures are classified into three types: A: extra-articular fractures, B: partial articular fractures;
Capitellum and Trochlea Fractures:
Bryan and Morrey\textsuperscript{14} classified capitellar fractures as Type 1, 2, and 3 depending on the involvement of the subchondral bone or compression. McKee and colleagues emphasized that these often involve a substantial part of the anterior trochlea.\textsuperscript{15-17} Ring and colleagues distinguished five patterns of articular injury based on each additional involvement to a fracture of the capitellum and the lateral portion of the trochlea, of the lateral epicondyle, posterior capitellum, posterior trochlea and medial epicondyle.\textsuperscript{11, 17, 18} Dubberley\textsuperscript{19} classified low articular fractures into those involving primarily the capitellum with or without the lateral trochlear ridge (Type 1), those involving the capitellum and the trochlea as one piece (Type 2), and those consisting of fractures of both the capitellum and the trochlea as separate fragments (Type 3). These fractures were further characterized with respect to the absence (A) or presence (B) of posterior condylar comminution.

**Imaging**
Distal humeral fractures are difficult to characterize and classify on radiographs.\textsuperscript{20} Radiographs have low sensitivity and negative predictive values. Preoperative computed tomography (CT) gives more information to assist in pre-operative planning.\textsuperscript{17, 21-23} Three-dimensional (3D) imaging has several potential advantages over radiographs and 2-dimensional (2D) computed tomography (CT).\textsuperscript{23, 24} Three-dimensional imaging seems more intuitive--structures look similar to what the surgeon sees in the operating room. In addition, the technique has been associated with improved identification of single fragments, articular surfaces, and fracture edges\textsuperscript{25}, which allows better preoperative planning in terms of implants and equipment while also facilitating the surgeon’s preparation. Physical models could be used as a medium for realistic surgical planning, customization of treatment devices, and detailed communication. Models could also be used extensively in educational settings, research, and implant development.\textsuperscript{26}

**Treatment of Distal Humerus Fractures**
The goals of treatment may be different for elderly patients who are debilitated, infirm, and dependent on others for care and those who remain healthy, active, and independent. In either case the aim of treatment should be to return the patient to his or her pre morbid status, as resourcefully and with as little risk as possible. In patients with limited functional demands, an adequately mobile pain free elbow may be achieved with limited morbidity with the so-called ‘bag-of-bones’
Treatment of active, independent, elderly patients and younger adults should account for the importance of motion and stability of the elbow joint to overall upper extremity motion. The vast majority of distal humerus fractures are displaced and operative treatment represents the best opportunity for preserving elbow function.29

The results of operative treatment improved as elbow anatomy, operative exposures, and techniques for securing small articular fracture fragments were better understood.30 Nevertheless, reconstruction of the complex articular anatomy is particularly challenging when small fragments, many limited non-articular surfaces, must be realigned and stabilized with sufficient security to permit functional aftercare. Certain fracture patterns and reconstructive problems remain particularly troublesome.29

Complications of Distal Humerus Fractures
Adverse events associated with complex distal humerus fractures can occur both during the injury itself and during operative treatment and include: failure to unite, malunion, loss of functional motion, ulnar neuropathy, osteonecrosis, infection and heterotopic bone formation.29-32 These can contribute to impairment and disability.30

The operative repair of an ununited distal humerus fracture is challenging, because the bone quality is typically poor as a result of previous failed operative fixation and disuse osteopenia.29 Contracted joint capsule amplifies the need for strong fixation to allow immediate mobilization after anterior and posterior capsulectomy.12, 33, 34 Heterotopic ossification is also challenging, because excision of the ectopic bone necessitates extensile exposure and may place several nerves at risk.35-42 Ulnar nerve dysfunction is a common consequence of operative treatment of fractures of the distal humerus and is difficult to treat.12, 34, 43

Outline of the Thesis
The general aim of this thesis is to investigate complex distal humerus fractures. In part I the implications of evolution on distal humerus anatomy are reviewed. The aim of part II is to better understand complex fractures of the medial column and low extra-articular fractures of the distal humerus. Part III is to evaluate various imaging methods of distal humerus fractures. Part IV is to review the complications heterotopic ossification, osteonecrosis and ulnar neuropathy. In part V, all chapters of this thesis will be reviewed in general perspective in a discussion and summary in the English and Dutch language.

Part I Introduction
In chapter 1 of this thesis the development of distal humerus anatomy over time is reviewed and a comparison is made between human distal humerus anatomy and 5 related species based on different ways of locomotion: the dolphin (aquatic), the bat (areal), the mole (fossorial), the gibbon (arboreal) and the lion (terrestrial, quadrupedal). Chapter 2 is a general introduction to complex distal humerus fractures.

Part II Complex Distal Humerus Trauma
Complex fractures of the medial column are the subject of chapter 3. In medial column fractures the lateral column remains intact. Single column fractures are uncommon in adults so very little has been written about medial column fractures. The aim of this chapter is to document the presentation, fracture patterns and prognosis of medial column fractures. Amongst 26 patients identified in the English language literature, only 2 had articular fragmentation. We reviewed the experience of 2 trauma centers with isolated medial column fractures in order to evaluate our hypothesis that these fractures often involve complex articular fragmentation.

Similar to medial column fractures, low transcondylar extra-articular distal humerus fracture -at the base of the olecranon fossa- are relatively uncommon in adults. Despite the rarity of these fractures, they are over represented in nonunion series. Chapter 4’s aim is to investigate the prevalence of low transcondylar fractures and the comparison of results to other extra-articular bicolumnar distal fractures. We hypothesize that these fractures may be more common that previously recognized and that they have a relatively higher risk of non-union.

Part III Evaluation of Distal Humerus Fractures
Distal humeral fractures are difficult to characterize and classify on radiographs. Plain radiographs have low sensitivity and negative predictive values. Preoperative computed tomography (CT) gives more information to assist in pre-operative planning.

Accurate preoperative radiological characterization of the fracture may facilitate management. Prior studies have demonstrated improved agreement in characterization and classification of various fractures with three-dimensional (3DCT) compared to two-dimensional computed tomography (2DCT) images and radiographs. Three-dimensional (3D) models are constructed based on CT images and can be held in the hand and may facilitate fracture characterization and surgical planning.

The investigation for chapter 5 used prospectively recorded intra-operative evaluation of distal humerus fractures as the reference standard for fracture type and characteristics. Diagnostic performance characteristics were calculated for 2D and 3DCT and 3D models with respect to this reference standard to test our hypothesis that 3D-CT images and models improve the reliability and accuracy of classification and diagnosis of specific distal humerus fracture characteristics as well as accurately predict treatment. In secondary analyses, the reliability of the classification and characterization of these fractures was assessed.

In chapter 6 we developed a method of measuring the anterior translation of the articular surface of the distal humerus in order to test the hypothesis that anterior translation of the distal articular surface of a distal humerus after open reduction and internal fixation after a distal humerus fracture correlates with elbow flexion. Quantitative measurements of fracture morphology may provide a more detailed understanding of fracture morphology, which could help with management decisions, implant choice, and implant development. In chapter 7 we test the
influence of quantitative evaluation on distal humerus fracture morphology. We hypothesize that bicolumnar fractures and capitellum and trochlea fractures create similar numbers of 1) fracture fragments, 2) small (difficult to repair) fragments, and 3) articular fragments.

**Part IV Complications**

Heterotopic ossification reflects a series of events that result in highly organized bone around the elbow joint. Loss of motion ranges from small limitations to complete lack of elbow motion or ankylosis.\(^9, 38, 39, 71-73\) For **chapter 8** we tested the null hypothesis that, controlling for other factors, patients with complete bony ankylosis and patients with HO causing partial limitation of motion have similar motion after elbow contracture release.

The blood supply of the capitellum is limited.\(^74-77\) Recent studies show the previously underestimated involvement of the posterior aspect of the lateral column in low articular fractures, which will likely compromise the blood supply of the anterior portion of the lateral part of the distal humerus.\(^19, 21, 22, 78\) **Chapter 9** documents a substantial rate of nonunion after an articular fracture of the distal humerus. We hypothesize that nonunion may be more common than previously noted, perhaps because we are including more complex fractures with lateral column injury and greater disruption of the blood supply.

The incidence of postoperative ulnar nerve dysfunction after open reduction and internal fixation of the distal humerus fractures has been reported as 0% to 51%,\(^29, 44, 57, 58, 79-112\), but the multifactorial prevalence of ulnar nerve dysfunction after open reduction and internal fixation of distal humerus fractures is not well understood.\(^108, 110\) In **chapter 10** the aim is to identify predictors of ulnar neuropathy after distal humerus fractures as ulnar nerve dysfunction is one of the most common complications of operative treatment of fractures of the distal humerus.\(^29\) We hypothesize that implant placement over the medial epicondyle and olecranon osteotomy influence the occurrence of ulnar nerve dysfunction.

**Part V General Discussion & Summary**

In **chapter 11**, all previous chapters will be put into perspective in a general discussion and summary in the English and Dutch language.
References

