BIOMECHANICAL EVALUATION OF OPTIMAL HUMERAL FRACTURE FIXATION DEVICES

D. Hughes[1], F. Nabhani[2] and S.Hodgson[3]

1. School of Science and Engineering, Teesside University, UK

2. Professor, School of Science and Engineering, Teesside University, UK

3. Dean of School of Science and Engineering, Teesside University, UK

ABSTRACT

The Glenohumeral joint poses one of the biggest challenges to an orthopaedic surgeon when compared to any other joint within the human body [1]. Finding the optimal treatment to suit each individual patient is crucial to his/her subsequent quality of life [2] but there is an urgent need to define more clearly the role and type of surgical intervention in the management of proximal humeral fracture [3]. This study aims to evaluate current humeral fixation techniques available to orthopaedic surgeons for their effectiveness at maintaining the integrity of the humerus across varied patient types, enabling full functional movement under physiological, cyclical loading and directly applied stresses. This is achieved using a finite element model of the Glenohumeral joint loaded with the in-vivo force mechanics of the joint. The FE model is validated against a mechanical test rig and current literature. Multiple tests are applied to the shoulder complex to investigate forces generated and effects on joint mechanics. These tests are based on activities of daily living with data collected using motion capture technology. As a result of the study it will be possible to make recommendations regarding the biomechanical fixation techniques of the proximal humerus for varying complexities of fracture, differing bone properties and populations in an attempt to find the optimal treatment to suit each individual patient. It also provides an opportunity to investigate how current fixation techniques are best used and look to advise on most effective applications.

KEYWORDS: Glenohumeral Shoulder Biomechanics

1. INTRODUCTION

The Glenohumeral joint poses one of the biggest challenges to an orthopaedic surgeon when compared to any other joint within the human body. The Glenohumeral joint is a modified synovial ball and socket joint, the kinematics are unique and do not represent the standard mechanics of a ball and socket joint such as the Hip [1].

As the glenoid fossa is considerably shallower than the acetabulum the range of motion (ROM) at the Glenohumeral joint (diarthrodial) is the largest of any joint in the human body [4]. The Glenohumeral joint is only one of four joints found within the shoulder region, the Scapulothoracic, Acromioclavicular and Sternoclavicular joints provide a moveable supporting frame to increase the ROM of the shoulder joint further giving it a full 6 Degrees of Freedom (DOF) [5].

As there are a plethora of muscles acting over the shoulder with little anatomical surface for attachment onto the proximal humerus the fixation techniques are limited in their application.

At present there are few areas on which multiple authors agree, most notably the optimal method of fixation as there are numerous options available for treatment of proximal humeral fractures [6] ranging from closed techniques that are minimally invasive (such as K-wire osteosynthesis), to open procedures with the use of conventional and fixed-angle plating systems, various intramedullary nailing systems, bone sutures and even primary shoulder arthroplasty [7,2,8]. However most authors agree on the importance of anatomic reduction and stable fixation to allow early range of motion [9] especially in young people with high demands [8].

Fractures of the humeral head account for about 4% to 5% of all fractures in adult patients [3,2,10,11] and 45% of all humerus fractures [10]. Proximal humeral fractures are about half as common as hip fractures [3] the overall incidence is about 50–100 fractures per 100,000, with an exponential increase from the fifth decade of life onward [2]. The male-to-female ratio varies from 1:2 to 1:5 in different publications [2] however proximal humeral fractures are the third most common fracture in elderly patients [9]. A review on Proximal Humerus Fracture Rehabilitation stated that "Proximal humerus fracture rates will continue to increase with the aging population" [24]. The findings of the review are supported by multiple authors [25,26].

In 2003, a review of the current interventions for treating proximal humeral fractures in adults was published in the Cochrane Database. The review incorporated evidence from 12 randomised controlled trials of treatment of proximal humeral fractures, involving a total of 578 patients, from single centre studies, conducted in five different countries. The authors concluded there is insufficient evidence from current randomised trials to determine which interventions are the most appropriate for the management of different types of proximal humeral fractures [3]. The findings of the review are supported by multiple authors [8,12,9,13] and continue to pose an ongoing problem. In particular there is a need for better information with regard to the optimal selection, timing and duration of all interventions [3].

Symptomatic shoulder disorders are common, their prevalence varying between 21% and 34% in community surveys [15,16,17], and their recurrence rate is high. Disability related to shoulder disorders was found in 30% of healthy subjects over the age of 65 years and was significantly associated with reduced movement [16].

Finding the optimal treatment to suit each individual patient is crucial to his/her subsequent quality of life [2] but there is an urgent need to define more clearly the role and type of surgical intervention in the management of proximal humeral fracture [3].

2. METHODOLOGY

The methods of biomechanical analyses performed by the manufacturers is unclear, however numerous authors have attempted to assess the biomechanical fixation techniques. The "standard" technique has been described by Chudik (2003) [7] and involves applying a uniaxial load onto a humerus orientated at 30° as this closely replicates the axial loading of the humerus under physiological loading. However, this technique is based upon literature dating from 1944 [14], the technique is employed by several other authors but the remaining authors do not substantiate the methodology they employ. To date several authors have loaded the humeral head under 6 DOF however none of these authors have loaded the humerus in this manner and tested fixation techniques of the shoulder region.

To more accurately define the failure and application of interventions for treating proximal humeral fractures in adults a more accurate test medium is required. In this study two methods were developed a mechanical model of the Glenohumeral joint representing the in-vivo mechanics and forces of the joint and a Finite Element (FE) model.

2.1 Mechanical Model

The mechanical test rig allows for accurate and detailed data collection on multiple tests. It is not a fully dynamic test rig in that the Glenoid is fixed however Kent (2006) [18] and Bryce (2008) [19], showed that a fixed Scaplothoratic plane can still create an “accurate and reliable 3D model” [19]. The frame has been tested for structural strength and a large margin of safety has been allowed. Synthetic bones are used with high similarity to human bone to generate accurate and valid results.

Tests carried out on the mechanical test rig are based upon work by Bergmann (2007) [20] who developed a proximal humeral prosthetic implant containing 6 strain gauges. These were implanted into four human subjects and forces in the arm were measured in over 50 different activities from the 4th to 7th postoperative month. This provides accurate in-vivo data which has been re-created within the mechanical test rig measured using a similar implant and strain gauge arrangement.

To date two tests have been simulated using the mechanical test rig looking at the forces involved in prosthetic proximal humeral implants. Displayed below are the two heads mounted in the synthetic bone and the original implant.

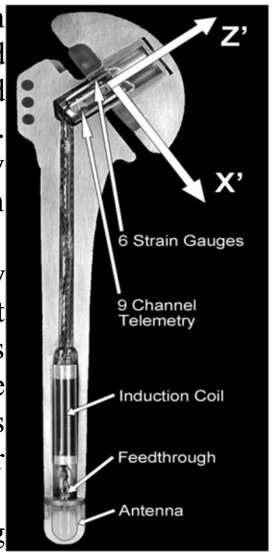

Figure 1 – Implant by Bergmann [20]

These are two different approaches to implant design, one long stem and the other a head replacement. Each is fitted with strain gauges to measure resultant forces in 6DOF.
Biomet the designers of the Copeland™ Humeral Resurfacing Head, state that using the shorter implant shown in figure 2 requires much less bone and cartilage removal, which makes it more conservative than total joint implants [21]. The Copeland™ implant's is also design to allow patients to potentially recover more quickly and with less pain [21]. Zimmer on the other hand have developed a long stem system. They have focused on the ability to replicate patient specific bone geometry with a flexible head. This reduces the time needed for a patient to adapt to anatomical changes imposed by a first- or second-generation implant that offered nothing more than an approximate fit [22]. Zimmer states that this allows a more advanced rehabilitation and an expanded radius of movement while placing fewer demands on the soft tissues and on the anchoring of the prosthesis [22].

The Copeland™ Humeral Resurfacing Head - Biomet	Zimmer - Anatomical Shoulder System
 **Figure 2 – Copeland Head[21]**	 **Figure 3 – Anatomical Shoulder [22]**

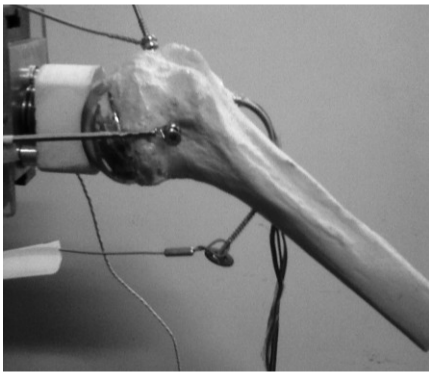

Figure 4 – Copeland Implanted with strain gauges.

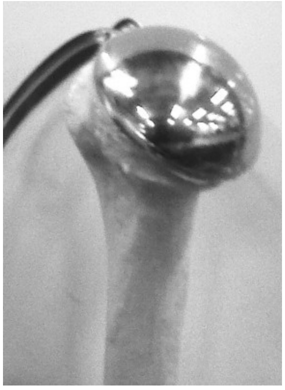

Figure 5 – Zimmer Implanted with strain gauges.

The implanted prosthetics with strain gauges fitted in a similar pattern to Bergman are shown above. This allows the measurement of x, y and z forces in the neck of the proximal humerus. These are fitted into a specially designed test rig which simulates the applied muscle forces and replicates the in-vivo mechanics of the Glenohumeral joint.

Both the implants are very high quality and each addresses a specific need within shoulder surgery and rehabilitation. This study will not attempt to comment on the design of the implants but at present illustrate the importance and capability of the testing medium to accurately compare different fixation methods and their effect upon forces generated within the joint, musculature and bones.

2.2 Finite Element Model

The finite element model currently has the two prosthetic implants modelled in MSC Marc Mentat and inserted into a 3D bone model with dimensions taken from CT scans produced for the Laboratory of Human Anatomy and Embryology, University of Brussels. The FE model like the mechanical model accurately represents the in-vivo conditions of the Glenohumeral joint. Muscular forces are loaded from the point of muscular insertion along the line of muscular action including the restraining forces the muscles have over the joint. The details of the FE model are detailed below:

1. Simulates physiological movement patterns to imitate Activities of Daily Living during cyclical loading patterns.
2. Applies loading representative of the in vivo physiological characteristics of the Glenohumeral joints.
3. Simulates the torsional loading / deforming forces applied to the proximal humerus due to the dynamic muscular stabilisation of the shoulder girdle along the line of action of each of the muscles.
4. Simulates shoulder centre postiorially and proximally applying large forces on the Supraspinatus and Subscapularis tendons to

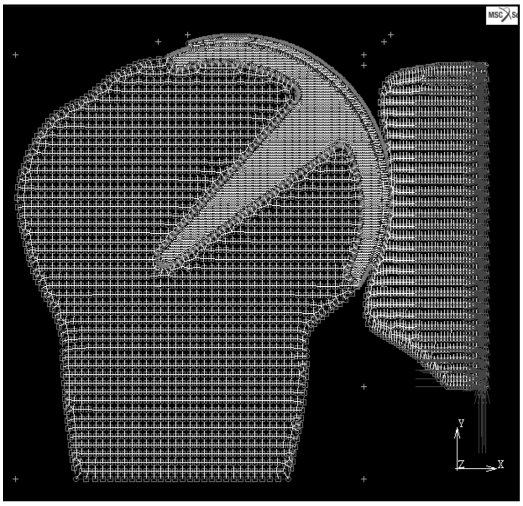

Figure 6 - FE Model Section with Copeland Head

investigate joint damage and tendon avulsion.
5. Replicates the 3 axe's of translation found at the Glenohumeral joint to reproduce the articular geometry of the Glenohumeral joint.

3. RESULTS

At the time of publication a full set of validated results are not available however the initial indications highlight the value of the testing taking place.

3.1 Mechanical Model

Tests carried out by Apreleva (2000) [23] shows the relationship between the angle of humeral abduction and the force applied at the Glenoid, the higher the abduction angle (degrees) the greater the force required to stabilize the joint (Newtons) [23].
The rig tested the contact forces at the Glenoid during abduction of the humerus. They were taken at intervals of $40^{o,}$ 60^{o} and 80^{o} abduction and compared to the validation data published by Apreleva (2000) [23].

The results from the test have been tabulated below in Table 1, also the values of the validation data have been included as well as a percentage of accuracy indicating how accurate the test rig was in replicating the results.

Abduction Angle (^{o})	Test Rig Result (kg)	Force Value	Data Value	Test Rig Accuracy (%)
40	2.1	214.06	204	95.3
60	2.9	295.61	306	96.6
80	3.4	346.58	349	99.3

Table 1 – Test rig contact force results during abduction.

3.2 Finite Element Model

Similar testing to that described above was carried out on the Finite element model; figure 5 shows the results of initial testing.

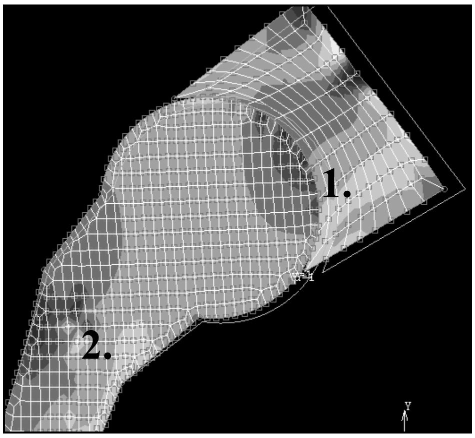

Figure 7 - Current FEA results showing contact forces, displacement and neck stress.

4. Conclusion

Though at the time of publication it is not possible to make any comment or conclusion on current humeral fixation methods this study shows the value of the described testing medium. The combination of the mechanical test rig and FE model enables extensive and destructive testing to be performed under in-vivo conditions. This makes the testing unique as it can be validated against true in-vivo data yet requires not test subjects and raises no ethical questions. The results above show that the test rig was able to very closely replicate the results of the validation data. The test rig was successful in applying in vivo physiological forces of the rotator cuff which in turn created contact forces between the humeral head and the Glenoid. The results measured a minimum accuracy of 95.3% and a maximum of 99.3%.

The finite element model clearly shows the forces being discussed in contact forces (highlighted point 1.) and transferred forces (highlighted point 2.) to the neck of the proximal humeral head.

This work is an important development in the Glenohumeral bio-mechanical field as it provides an accurate in-vitro test rig based upon actual in-vivo data collected by Bergman. This will allow for more accurate testing and destructive tests including fracture rehabilitation and accident simulations.

Future work on this study will include further validation of the test medium and then a comprehensive analysis of all fracture fixation techniques under different physiological conditions. Testing will also extend to the cause of fractures and sports injuries. The use of the FE model will allow easy comparison of different bone properties and high stress points. This test medium will not only provide an assessment of current techniques but also advise on and develop new ones. The test rig is also designed in such a way as to allow testing on any ball and socket joint so testing on the hip etc.

This study has shown the effectiveness of the described method in accurately different fixation methods and their effect upon forces generated within the joint, musculature and bones. As a result of the future studies it will be possible to make recommendations regarding the biomechanical fixation techniques of the proximal humerus for varying complexities of fracture, differing bone properties and populations in an attempt to find the optimal treatment to suit each individual patient. It will also provide an opportunity to investigate how current fixation techniques are best used and look to advise on most effective application.

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