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A Methodology for Biomechanical Assessment of Proximal Humerus Fractures Using an Integrated Experimental and Computational Framework

Ali Jabran[a*], Lei Ren[a], Chris Peach[b], Zhenmin Zou[a]

[a]*School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M13 9PL, UK*
[b]*University Hospital of South Manchester, Southmoor Road, Wythenshawe, Manchester, M23 9LT, UK*

* Corresponding author. *E-mail address: ali.jabran@postgrad.manchester.ac.uk*

Abstract

Fractures of proximal humerus are currently the third most common fractures in patients over the age of 65 years. An integrated experimental and computational framework is proposed for the development of novel proximal humerus plates with enhanced biomechanical and clinical performance. It involves in vitro mechanical testing of leading proximal humerus plates using 3D laser scanners as an assessment modality to allow 3D comparison of different plate-humerus constructs during tests. This paper presents the methodology and shows the preliminary work from the 3D scanning to be used for computational modelling.

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Keywords: 3D laser scanning, proximal humerus, biomechanics, locked fixation

Introduction

United Kingdom's population is living longer than ever before, with the number of centenarians increasing approximately 73% over the last decade [1]. Ageing has become one of the forefront pressures that threaten to overwhelm the National Health Service (NHS) during the current healthcare crisis. With 17% of the total UK population now over the age of 65, by 2031, the population of the 65-84 age group is predicted to increase by 50% and those aged over the age of 85 will double by 2031 and treble by 2071 [2].

Fractures of proximal humerus are currently the third most common fractures in patients over the age of 65 years [3]. With ageing population and increasing prevalence of osteoporosis, incidence of these fractures is projected to increase up to 300% over the next 30 years [4]. After the fractures, the elderly face high risk of prolonged loss of shoulder function and immobility, preventing them from performing activities of daily living.

Management of severely displaced fractures remains a challenge due to complications such as osteoporosis that are common in the elderly. Non-operative approach has been shown to be troublesome for these fractures as it could lead to shoulder deformity and stiffness. Proximal humerus plates (PHPs) are a very common operative treatment modality which have risen in popularity in the recent years since the development of locking technology. However, clinical results on the use of these plates report high incidences of complications such as varus malreduction which severely affect the patients' experience and are a major challenge to successful recovery. It is therefore crucial to develop a framework which allows development of novel plates that have enhanced biomechanical and clinical performance.

Methodology

We propose such a framework which can be divided into two phases (Fig. 1). The first phase involves in vitro tests aimed to determine the biomechanical performance of the leading proximal humerus plates in the clinical setting. Upon completion of these tests, a finite element model (FE) simulating the loading conditions of these in vitro tests will be created and validated from the obtained test results.

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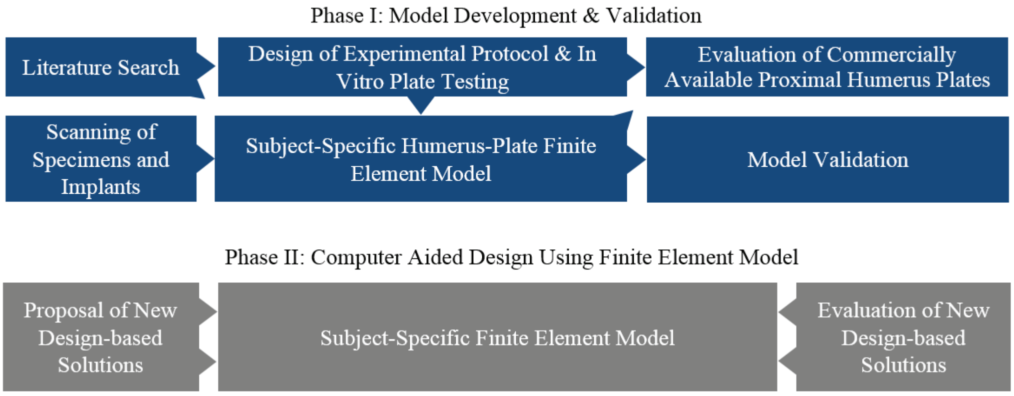

Fig. 1. Key milestones in the two phases of the combined experimental and computational framework.

In the second phase, the validated FE model will be used to test proposed plate designs. These designs are to be based on the results from the in vitro tests and the developed understanding of the mechanical and clinical aspects of the fractures in collaboration with an orthopaedic surgeon specialising in proximal humerus fractures.

Results

In vitro tests involve osteotomising of two-part transverse proximal humerus fractures on synthetic humeri (Sawbones, USA). A second cut is made 21 cm distal to the apex of the humeral head. Fractures are treated with one of the three plates: PHILOS (Synthes, USA), S^3 (Biomet, USA), Equinoxe Fx (Exactech, USA) and loading them under a selection of loads such as cantilever bending.

Three dimensional (3D) laser scanner, (EXAscan, Creaform, Canada), is used to perform 3D scans of the plate-humerus construct at regular intervals during the course of loading. Scans are both contactless and non-destructive to the specimen with duration of each being approximately 5-10 minutes. Live acquisition of the 3D data is achieved using Creaform VXelements software. The scans (.stl format) are exported to Geomagic Studio (3D Systems, USA) where they are processed (trimming, smoothing and alignment). 3D comparison of the scans is then made using Geomagic Qualify (3D Systems, USA), allowing visualisation of the 3D deformation of the test scan against the reference scan.

For example, for cantilever bending tests, 3D scans of the specimen were captured at regular intervals during the tests. Fig. 2 shows resultant (of x, y and z axes) deviation of the specimen at the end of the bending test with reference to a scan performed before any loading. While the head of the humerus is fixed and the load applied at the distal end, the 3D comparison allows the visualisation of the deviation across the specimen surface. In this case, a relatively large deviation is visible at the distal and gradually, near the plate, deviation is smaller due to implant support. 3D scans are also used to measure fracture gap at multiple points on fracture surfaces.

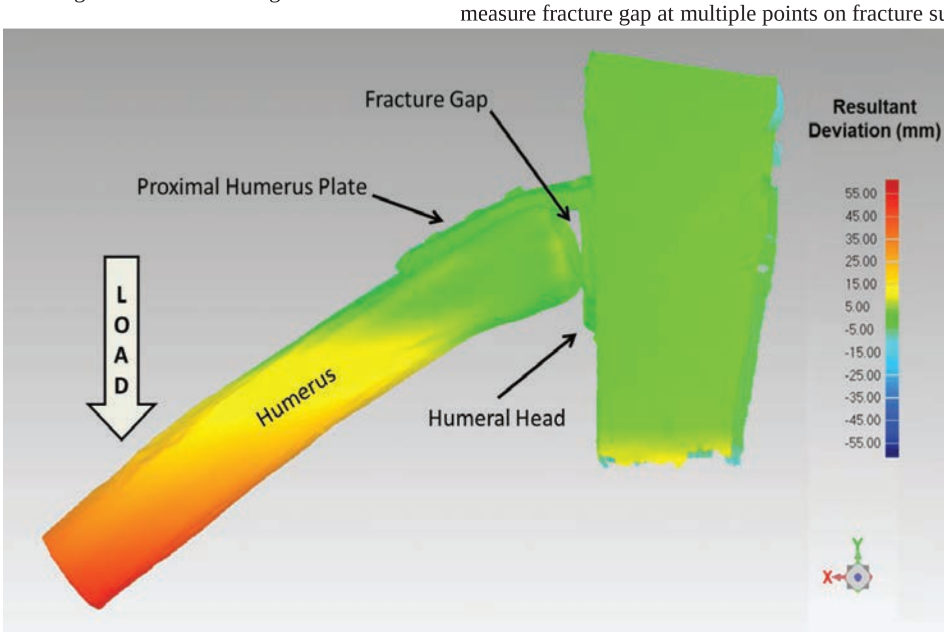

Fig. 2. Typical 3D comparison map from 3D laser scans showing resultant deviation of plate-humerus construct under cantilever bending test.

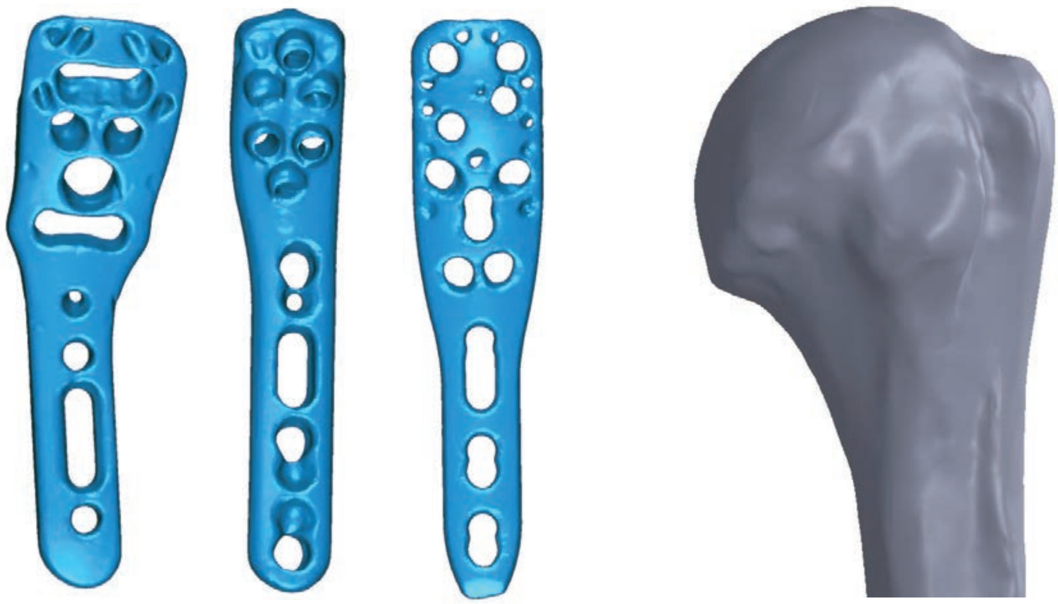

Fig. 3. (L to R) 3D models of the proximal humerus plates: Equinoxe Fx, S^3 and PHILOS scanned with Faro Arm. (Far right) 3D scan of humerus from EXAscan 3D laser scanner.

For simulation, 3D scanner has been used along with Faro Arm (Faro Technologies , USA) and several reverse engineering techniques to develop CAD models of humerus and PHPs. 3D scans (.stl files) are imported into Geomagic Studio where they are processed using the same tools used for the plate-humerus construct. Processed .stl files are then converted into parametric solids in SolidWorks so that their features can be modified for finite element analysis. (Fig. 3).

Discussion

As for the biomechanical studies of proximal humerus, several techniques have been employed in the literature to investigate the behavior of the plate-humerus constructs during the tests. The most common of such techniques is the performance of 3D motion analysis (often ultrasound based) to measure the relative motion among the fracture fragments and between the fragments and the plate [5-8].

In addition to this, fluoroscopic assessment (using C-arm) which is often conducted for qualitative analysis was used by Roderer et al. [9] to determine the migration of humeral head after set number of load cycles. One of the key limitations of the 3D laser scanners is that they only scan the external features. CT scans, on the other hand, can reveal the interiorities, allowing us to further explore the failure mechanism and help make better design decisions [10].

Where 3D scanning stages in this study take approximately 5-10 minutes, the time and accuracy is largely dependent on factors such as the user's expertise and scanner's hardware and software. To our knowledge, 3D scanners have not been used in literature at least in the literature on proximal humerus fractures. Thus, this study will also help standardise a protocol for incorporation of 3D scanning in biomechanical studies.

Similarly, Mathison et al. used Digital Imaging Correlation (DIC) to not only determine the relative movement of fracture surfaces but also the local strain across the surface of the specimen [11]. To achieve this, speckling pattern was applied to the specimen surface at the start that acted as the reference point. During the course of loading, pictures of the specimen were taken which allowed the computation of the relative displacement of the speckles due to the applied load translations.

Another notable technique is the use of acoustic emission (often employed in civil engineering applications) for direct measurement of the number, amplitude and distribution of microcracks formed on humeri during testing [12].

As far as the data acquisition is concerned, 3D motion analysis is at a clear advantage over the 3D laser scanner used in this study, as the former allows real time acquisition of data. The latter only allows scanning of stationary objects and thus restrict us to pause our tests at regular intervals to scan. In this respect, real time 3D laser scanning could be a potential investigation for future allowing us to more clearly monitor the transitions between different stages of failure mechanism.

Conclusion

Future work on laying this framework and developing a validated model will allow development and quantitative assessment of novel plates without the need of extensive in vitro biomechanical tests. Thereby, from the industrial point of view, the time and cost of implants' design process will be significantly reduced while avoiding challenges such as ethical issues and inter-specimen variability that are found in in vitro and in vivo tests.

3D laser scanning is a powerful tool that allows both non-destructive and measurement of 3D surface deformation across specimen surface as opposed to most traditional sensors and gauges.

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