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DESIGN AND DEVELOPMENT OF NOVEL ANATOMICAL SCAPULAR FRACTURE FIXATION PLATES: POPULATION-BASED AND FRACTURE-FOCUSED DESIGN

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ABSTRACT

Surgical fixation is a recommended procedure for displaced and unstable scapular fractures to restore anatomical alignment and articular congruency of the fracture fragments. Anatomically Precontoured scapular plates are designed to guide the fracture reduction, used as a template, and stabilize the fixation. However, anatomical variation of the scapula and the complexity of the fracture patterns limit the usability of these plates. The aim of this study was to design and develop population-based novel anatomical scapular plates. An average three-dimensional (3D) scapular bone model was developed from 22 healthy cadaver scapulae of target population (South Africans) using Statistical Shape Modelling (SSM) method. The fracture region of interests was identified using a fracture map of 70 scapular fracture patterns. Using the average 3D scapular model as a reference template and the common fracture zones as a reference fracture pattern, anatomical plates were designed for the critical scapula fracture patterns. Lateral border, medial border, glenoid fossa & neck, glenoid fossa & body, and acromion plates were designed. Combining 3D CT image based statistical shape modelling and fracture pattern analysis with CAD is relatively quick and efficient method to develop clinically meaningful population-based anatomical plates.

Key words: Scapula fractures, Anatomical plate, Population-based design, Statistical shape model, Fracture patterns

1. INTRODUCTION

Open Reduction Internal Fixation (ORIF) of scapular fractures is often challenging due to unfavorable scapula anatomy, complex fracture patterns, and limited bone thickness for implant placement and fixation[1, 2]. The fixation process demands accurate anatomical reduction and stable fixation to facilitate proper healing and to restore full range of shoulder movement. Different implants mainly plate and screws, screws alone and cerclage wires are used depending on the size of the fracture fragments [3]. The commonly used type of plates includes reconstruction plates, Direct Compression Plates (DCP) or Locking Compression (LCP) type, and T-type or L-type mini fragment plates [3, 4]. When straight DCP and reconstruction plates are used, intraoperative bending is required to fit the scapular anatomy which is time consuming and entirely depend on individual surgeons' skill. Moreover, the repeated bending and twisting action could induce residual stress leading to implant failure. Reports from surgical outcome results indicated that hardware removal rate related to either implant failure or discomfort are between 7% to 9% [3, 5].

Anatomically Precontoured scapular plates are provided to specific anatomical regions [6]. The design of these plates replicates the scapular anatomy and are serve as a template to guide fracture reduction. They are also used to save operating time by minimizing or avoiding the need for intraoperative plate bending. However, due to anatomical variations of the scapula and multiple scapular fracture patterns the available scapular plates do not fit well the intended anatomical regions of the scapula [7] and could not accommodate critical scapular fracture patterns [8]. Three-dimensional (3D) statistical shape model (SSM) based anatomical plate designs are recently introduced to optimize the commercial anatomical plates [9, 10] or to design new anatomical plates [11] to improve population level anatomical variability of the target bone. However, in the case of scapular fractures not only the bone anatomy which affects the design of anatomical plates but also the fracture patterns. Consequently, surgeons often use generic plates and should bend them intraoperatively to fit the scapula anatomy. The aim of this study is to design and develop population-based novel anatomical scapular plates considering the common scapular fracture patterns.

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2. MATERIALS AND METHODS

2.1 Developing population-average model of the scapula

To incorporate population-level anatomical variabilities of the scapula, an average 3D scapula model was developed from the South African population using Statistical Shape Modelling (SSM) method. The CT images of 22 healthy cadaveric scapulae, obtained from previous study in our group, were used to create the model. First the 3D surface models were reconstructed from the CT images of respective scapula using image segmentation method and the surface meshes were refined. Next, all the datasets were rigidly aligned to a common reference using Procrustes analysis. The rigid alignment was guided by 12 common landmark points both on the reference and the targets. Then to create correspondence between the datasets, a free-form deformable model (FFDM) was created and iteratively deformed to fit each datasets using non-rigid Iterative Closest Point (ICP) algorithm. Finally, the statistical shape model of the scapula was developed using Principal Component Analysis (PCA) as shown in figure 1.

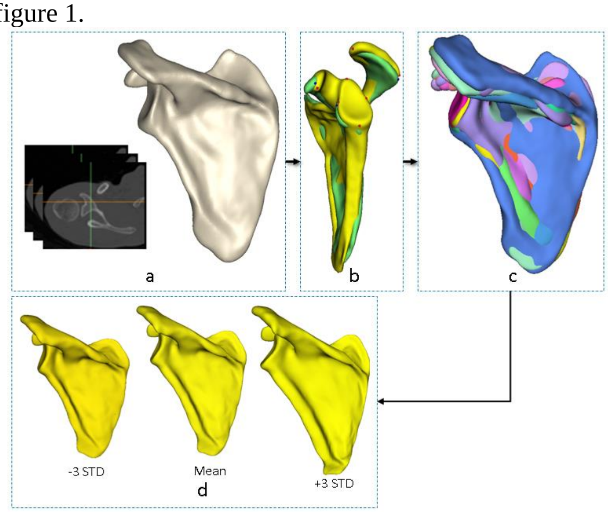

FIGURE 1: Process of developing population-average 3D scapula model a) The scapula 3D surface model reconstruction from CT images b) Rigidly aligning targets on a common reference using landmark points c) Establishing correspondence between datasets after fitting a deformable model to each target d) Statistical mean 3D scapula with the first mode of variation Only the mean shape was used as representative 3D template for the target population.

2.2 Identifying frequent scapular fracture patterns

Fracture and heat maps were used to identify the anatomical regions of frequent scapular fracture patterns. The CT images of 70 scapular fractures were used to create the fracture maps. First, the CT image files in DICOM (Digital Imaging and Communications in Medicine) format were imported into Mimics 16.0 (Materialize NV, Leuven, Belgium). Then the 3D reconstruction and fracture reduction were performed to align the fracture fragments to the correct anatomic position. Finally, the fracture lines were transcribed, and superimposed on a heathy template to create the fracture map. Additionally, heat maps were created by digitizing the fracture lines to show the intensity of the fracture patterns.

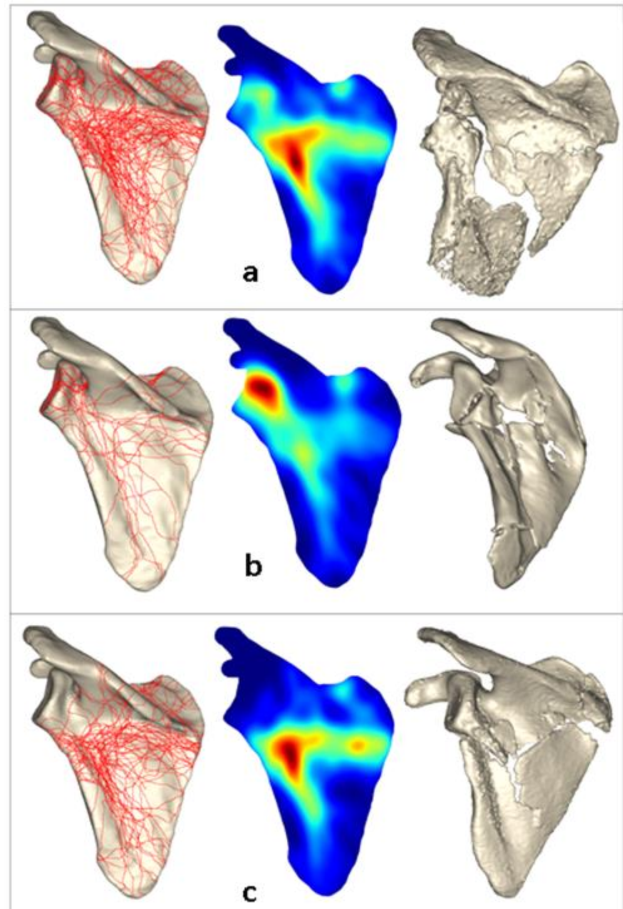

FIGURE 2: Fracture and heat maps illustrating the distribution and frequency of scapula fracture patterns, respectively, in a) All fracture cases (N = 70), b) Intraarticular fractures (N = 24), c) Extraarticular (scapula body and neck) fractures (N = 43)

The number of fracture lines crossing through the exit zones were recorded and statistically analyzed in three categories namely i) All the 70 fractures, ii) Intraarticular glenoid fractures with or without body extension, and iii) Extraarticular (scapula body and neck) fractures. The distribution and frequency of the fracture patterns in the three fracture categories were illustrated graphically using the fracture and heat maps, respectively, as shown in figure 2. For each fracture categories a real fracture cases were selected to represent respective categories and to be used as a “reference fracture line” for the design of anatomical plates as shown in figure. The detail procedure of this section is available in our previous study [12].

2.3 Developing surface and solid features of the anatomical plate

Using the population-average 3D scapula model (Figure 1.d-middle) as a reference template and the critical fracture patterns (Figure 2) as a reference fracture patterns, the placement of the plates was decided. Consequently, the plates were designed for lateral border, medial border, glenoid fossa & neck, and glenoid fossa & body fracture patterns. However, the design method is illustrated using the lateral border plate as follows. First, the average 3D scapula mesh surface was converted to CAD (Computer aided design) surface to create the plate profiles. The geometric CAD surface was created by extracting the mesh surface from the anatomical region of interest and converting to CAD surface using profile curves and surface loft in Solid Works. Then the plate surface was created by projecting the plate profile and cutting the geometric surface. The plate surface profile parameters are length (L), width (w), radius of curvature (R), screw holes, and distance between the screw holes. Finally, the plate solid feature was generated by extruding the plate surface with a constant thickness (t). The detail steps are shown in figure 3.

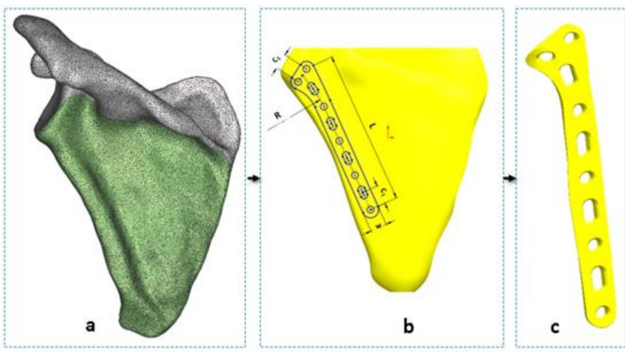

FIGURE 3: Steps in developing anatomical scapula plates a) Extracting mesh surface on the anatomical region of interest b) Creating the CAD surface from the mesh surface, creating the plate profile and projecting on the CAD surface c) Crating the solid anatomical plate by cutting the CAD surface with the projected plate profile and extruding the plate surface with a thickness (t)

3. RESULTS AND DISCUSSION

Combining 3D image-based fracture analysis, 3D statistical analysis and CAD methods, a total of five anatomical scapular plates with two size options (large and small) were designed to the lateral border, medial border, glenoid fossa & neck, glenoid fossa & body, and acromion fractures. The medial and lateral border plates are a modification of the commercial anatomical scapular plates [6] by optimizing to the target population. The glenoid fossa & neck, glenoid fossa & body, and acromion plates are novel plates. These plates were able to accommodate most common intraarticular glenoid and extraarticular (scapula body and neck) fractures.

The qualitative plate fitting and fracture fixability evaluation revealed that the novel plates suitably fitted the intended scapular anatomical regions. In figure 4, the lateral border plate is fitted on a reduced typical scapular body fracture case. Three screw holes are available to fix the proximal fragment which is a requirement for stable fixation.

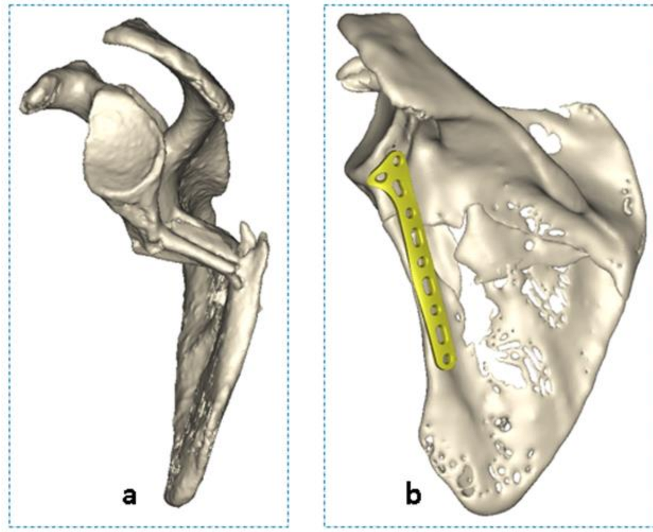

FIGURE 4: Qualitative plate fitting and fracture fixability evaluation of the lateral border plate a) Displaced lateral border fracture, b) Anatomical lateral border plate placed on virtually reduced scapula body fracture

Furthermore, the plate prototypes were produced, and the fitting and fracture fixation were qualitatively evaluated using 3D printed fractured scapulae. Figure 5 shows the qualitative evaluation of the lateral border plate on (a) left scapula and (b) right scapula body fracture cases.

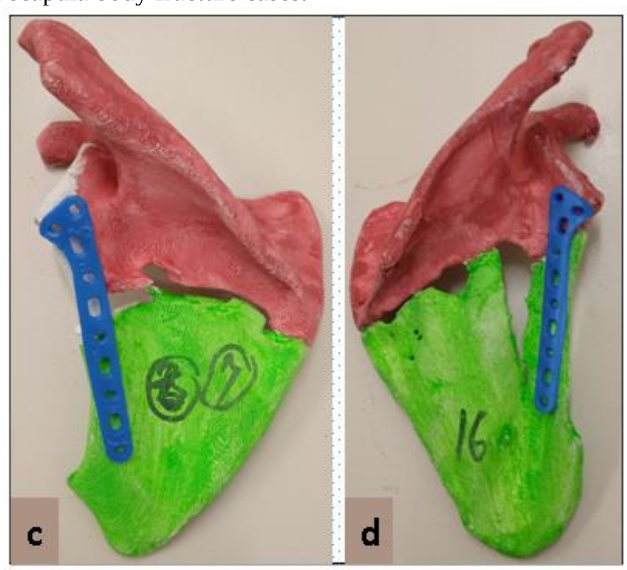

FIGURE 5: Qualitative plate fitting and fracture fixation evaluation of the lateral border plate on typical scapula body fracture cases a) Left scapula body fracture b) Right scapula body fracture

Unavailability [1] or poor fitting [7] of the commercial anatomical scapular plates left surgeons with no option and they forced to use either straight reconstruction plates by bending intraoperatively [5, 13] or anatomical plates designed for another bones [14, 15], which may result in complications related with either plate discomfort or failure [3]. In this regard, the novel scapular plates could be a better option to accommodate the fracture variants and better fit the scapula anatomy.

The limitations of our study are qualitative evaluation of plate fitting and fracture fixability. The usability of anatomically contoured plates can be evaluated quantitatively measuring the plate-bone distance. Future study will focus on validating the plate fitting and fracture fixability quantitatively and verification of the biomechanical performance of the novel plates.

4. CONCLUSION

Combining 3D CT image based statistical and fracture patterns analysis with CAD is quick and efficient method to develop clinically meaningful population-based anatomical plates. The method is convenient for design changes and could be applied for any bone type.

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