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BIOMECHANICAL EVALUATION OF HUMAN HUMERUS AND SCAPULA BONE: A REVIEW

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Abstract- This review explores current concepts in the biomechanical aspects of the various humeral injuries, reviewing the innovations, techniques and outcomes for the most common method of treatment. It is useful in the optimization of loads during different activities. Various methods are proposed to analyze the loading of the shoulder. Different datasets are taken from various patients either having pain in their shoulder or some accidental cases were considered, who suffered from dislocations of the glenohumeral joint or the proximal humeral fractures and then the injuries were examined. Biomechanical analysis was done for the fixation of humeral fractures. Comparative biomechanical analysis considering different implants was also done. The behavior of the humerus bone under the physiological load conditions and the straining of the bone and implant were analyzed.
Key words- Biomechanical Analysis, Glenohumeral (GH) joint, Humerus Bone, Proximal Humeral Fractures.

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Introduction

Humerus is the bone of the human upper arm and is the second most common long bone known. Proximal humeral fractures account for four to five per cent of all fractures and are about half as common as hip fractures. In contrast to the hip and knee joints, information concerned with the mechanical properties of the scapula and humerus is scarce. Substitution of correct mechanical properties into finite element (FE) models is extremely important to the understanding of the mechanical behavior of the joint elements. Such information is crucial to the design of prosthetic implants and representation of pathological conditions [4]. The shoulder is the most movable joint in the body. However, it is an unstable joint because of the range of motion allowed. This instability increases the likelihood of joint injury, often leading to a degenerative process in which tissues break down and no longer function well. The shoulder joint is composed of three bones: the clavicle, the scapula, and the humerus as shown in Figure - 1. The humerus provides support and structure for the muscles of the upper arm. The smooth, dome-shaped head of the bone lies at an angle to the shaft and fits into a shallow socket of the scapula also known as shoulder blade to form the shoulder joint. Below the head, the bone narrows to form a cylindrical shaft. It flattens and widens at the lower end and, at its base and joins with the bones of the lower arm, the ulna and the radius, to make up the elbow. The scapula is a large, flat, triangular bone with a very complex structure. The humerus articulates with the scapula at the GH, representing a ball and socket joint. The scapula is subject to a number of muscle, ligament and joint reaction forces during elevation of the arm. The primary function of the scapula is two-fold. On the one hand it offers an additional joint, so that the total rotation of the humerus with respect to the thorax can increase. On the other, it is a large bone, where the muscles have large lever arms with regard to the sternoclavicular (SC) and the acromioclavicular (AC) joint. The shape of the scapula provides large moments about the SC and the AC joint [26]. One method to analyze the loading of the shoulder is biomechanical modeling [15]. A computationally efficient and accurate 3-D Finite element (FE) model of a natural scapula and humerus is required to study the load transfer mechanism. Anatomically accurate finite element model of humerus bone with accurate geometry and material properties are retrieved from computed-tomography (CT) scan data. The material properties all elements and thickness of shell elements were based on the CT scan data [26]. FE models of long bones constructed from CT data are emerging as an invaluable tool in the field of bone biomechanics. However, the performance of such FE models is highly dependent on the accurate capture of geometry and appropriate assignment of material properties [7]. The uncertainties in modeling the geometry and the material properties of a human bone affect the predictions of a FE model derived from CT data. Finite Element Analysis (FEA) is a technique that reconstructs stress, strain and deformation in a digital structure.

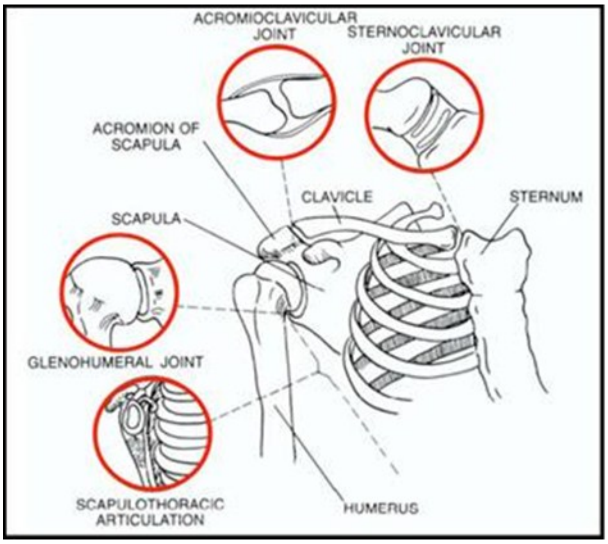

Fig. 1- Shoulder complex-bones and joints [8]

Review of Literature

Ten shoulders are harvested from fresh adult cadavera and are mounted to a vertically oriented aluminum frame by two threaded steel rods through the scapula. The center of glenoid surface laterally and the superior and inferior angles of the scapula medially are aligned with a vertical plane which is referred to as the scapular plane. Steel wire cables are attached to the humerus with a screw. The effect of various force patterns on the GH joint elevation is studied [22]. Nine fresh-frozen human GH joint specimens are used. The scapula and humerus are mounted in polymethylmethacrylate. The GH loading apparatus is set in which a central manifold with twelve rigid pipes extending from its sides and at the ends of each pipe is an air nozzle. Three mutually perpendicular coupled moments are applied to the humerus simultaneously. The humerus is loaded in abduction; extension and external rotation [17].Analyses of humeral head translation during passive and active elevation by applying an open Magnetic Resonance (MR) technique and 3-D digital post processing methods are applied. Fifteen healthy volunteers are examined with an open MR system at different abduction positions under muscular relaxation and during the activity of shoulder muscles. After segmentation and 3-D reconstruction, the center of mass of the glenoid and the midpoint of the humeral head are determined and their relative positions are calculated [14]. An analytical model of the human GH joint is developed to predict GH kinematics and investigate how the GH capsule and articular contact between the humeral head and the glenoid stabilize the joint. This is performed during a simulation of an apprehension clinical exam or the cocked phase of throwing, when the humerus is susceptible to anterior instability or dislocation. Six equilibrium equations are solved for the position and orientation of the humerus. The center of the humeral head translated posteriorly and superiorly with external rotation [16]. Three methods to determine the GH joint rotation centre in vivo are tested. Subjects performed humeral movements; a 3-D electromagnetic tracking device registered the motion of the humerus with respect to the scapula. For the first method to estimate the GH joint rotation centre five scapular bony landmarks served as input to regression equations. The second method fitted a sphere through the humeral position data and the third method calculated the rotation centre determining an optimal helical axis [20]. Four fresh specimens from cadaver arms are fixed at the scapula and fitted with electromagnetic sensors. Each arm is moved in different directions and the orientation of the humerus is recorded and active humerus is moved about the GH joint in abduction, adduction, flexion-extension and internal-external rotation directions. GH rotation center is calculated and the radius of the humeral head is estimated by fitting a sphere. These two methods for the calculation of the GH rotation center are then compared [13]. A tubular surrogate humerus is produced with dimension and strength matched to that of the human humerus. Two plastic tubes simulate the broken humerus and a slot is machined into two sides of each of the tubes. The material selected is nylon 6, 6 with thirty percent glass fiber reinforcement for which the internal diameter was taken as thirteen millimeter. A three point bending test is conducted by the way of validation. This test confirmed that the surrogate tube closely matched the humerus in terms of flexural rigidity [2]. A 3-D FE model of the natural scapula is developed, using CT data and shell-solid modeling approach. The outer cortical bone is modeled using two-layered triangular shell elements, the mesh generation and the solutions are obtained using ANSYS. The forces are found to be higher during 90º abduction. High tensile and compressive stresses are generated in the thick bony ridges of the scapula, like the scapular spine, lateral border, glenoid and acromion [26]. A study on the humeral torsion is done considering five hundred humeri collected from the various medical colleges of Gujarat. The angle of humeral torsion is measured by a method described by Krahl & Evans in 1945. The maximum, minimum and mean angle of torsion, the lengths and the circumference of the shaft in the left and the right side of the humeri are found. Comparison of torsion angle as measured by different workers in different races is done [27]. A new concept for prosthesis fitting of trans -humeral amputees is introduced. A Humerus-T-Prosthesis is cemented into the distal end of a human cadaver humerus using Palacos R-40 cum gentamicin bone cement. The bone specimen with the prosthesis is mounted on a jig in a MTS Bionix servo-hydraulic testing machine and subjected to alternating axial and torsional loading until failure of the fixation of the stem. Three patients are included in the approval of the new concept [11]. Six embalmed specimens of the shoulder are obtained from six human cadavers. Using a testing apparatus, the range of internal and external humeral rotation is assessed in an arc of GH elevation in the scapular plane with steps of 15º in six isolated shoulder joint specimens. Above 60° GH elevation, tightening of the inferior posterior GH joint capsule prevented both internal and, increasingly, external humeral rotation [19]. The biomechanical stability of a newly developed humerus nail Sirus for the treatment of fractures of the proximal humerus is analyzed in comparison to established systems. Three groups i.e. Sirus versus Proximal humerus nail (PHN) with spiral blade, Sirus versus PHILOS plate and Sirus versus 4.5 mm AO T-plate with four humeri samples each are considered and the bending and torsional loading are applied subsequently at each sample then a comparative biomechanical analysis of intra and extramedullary implants is done [6]. The wear in the prosthetic shoulder in association with design parameters is done in which the ANATOMICA ultra high molecular weight polyethylene glenoid component is used. The humeral head is modeled as a rigid spherical surface with joint reaction forces applied to the center of mass based upon the van der Helm (1994) for unloaded abduction of the humerus from 0° to 180°. Peak GH reaction force applied during abduction is 406 N. Medial and inferior borders of the scapula are fixed. Polyethylene thickness did not affect volumetric wear rates and metal backing only appeared to increase the contact pressures [5]. A biomechanical model to compare four osteosynthesis techniques for stabilizing supracondylar humerus fractures in children is developed. The pseudo fractures are then stabilized by crossed k-wires, elastic nailing, a fixateur extern with either k-wires, or Schanz screws. Stiffness values in flexion and extension and torsion are measured with static loading. No significant differences are found with static loading. With cyclic loading all methods showed an irreversible torsional deformation less than 20°. Crossed k-wires and elastic nailing showed significantly lower reversible torsional deformation than the external fixateurs [1]. Nine cadaveric shoulder specimens are mounted on the testing apparatus with the joint in the neutral position and at 30°, 60°and 90°GH abduction in the coronal, scapula and 30°forward flexion planes. The highest rotational range of motion for the joint was 140° for 71.0 Nm at 30°GH abduction in the scapula plane. The range of motion shifted towards external rotation with increasing levels of abduction. The results provide the optimum loading regime to pre-condition shoulder specimens and minimize viscoelastic effects in the ligaments prior to laxity testing [10]. Contact forces and moments are measured in vivo using telemeterized shoulder implants. Mean total contact forces from four patients during eight activities of daily living are considered. Lifting a coffee pot with straight arm caused a force of 105.0 percent body weight (BW) while setting down the coffee pot in the same position led to higher forces. The data suggest that patients with shoulder problems or during the first post-operative weeks after shoulder fractures or joint replacements should avoid certain activities encountered during daily living [23]. Eight GH joints are obtained from four cadavers from whom humerus and scapula are harvested. Data are collected at four humeral angles - 30°, 60°, 90° and 120° of elevation in the scapular plane. Humeral head net translation is calculated by manual digitization and contour registration methods and then the accuracy is measured. Each scapula and humerus are secured in a customized jig, that allowed for control of humeral head translations and a vise that permitted rotations of the scapula about three axes. The root mean square error between known scapular image and rotated image is 0.7° [18]. Twelve composite bones are taken and separated into four groups of fractured bones. Three types of implants used are locked plate, locked nail and DCP - buttress plate. Compression tests are performed with forces up to 5000 N. The angular displacement for internal and external rotation is taken as twelve degrees. LCP is proved to be more rigid implant for internal and external rotation whereas locked nail seems to be least rigid implant [24]. Twelve human humeri from twelve cadavers and ten fresh-frozen bovine and ten ovine humeri are used. The bone mineral density (BMD) of the humeri is measured. For biomechanical testing, the Zwick Universal Testing Machine is used. After this the microcomputed tomography and statistical analysis is done. The ultimate failure load seems to depend mainly on the cortical thickness and on the subcortical trabecular bone quality [21]. Three dimensional model of the femur bone is developed for FE analysis, the data is in DICOM image format which is obtained from the CT scan. After creating the model, a surface mesh is generated in MIMICS 10.01; this surface mesh is then imported in ABAQUS 6.10 where it is converted into the volumetric mesh. Material properties are assigned in ANSYS 12.0. The boundary and loading conditions are applied to the model and the FEA analysis is done to analyze the behavior of the femur bone [25]. Forces and moments in the GH joint of six patients during forward flexion and abduction of the straight arm are measured. The peak forces and, the maximum moments varied inter-individually to a considerable extent. Forces of up to 238 percent BW and moments up to 1.74 percent BW are determined. For elevation angles of less than 90° the forces agreed with many previous model-based calculations. When the exercises are performed at a higher speed, the peak forces decreased [12]. The position and orientation of the humerus with reference to the scapula is obtained using the two sequences for position of rest, 30°, 60°, 90° and 120°. Then a comparison of the description of GH motion is made using the two sequences. An electromagnetic tracking system collected data from ten healthy individuals while raising their arm and differences are found in the description of angular position data between the two sequences [28]. Thirty six major cadaveric, long bones including humerus, radius, femur and tibia which cover a wide range of bone sizes are tested under three-point bending and torsion. The strain gauges are attached on the bone surface based on the results of the three point bending and torsion FEA. First a quasi-static three point bending test of each bone specimen is conducted using a mechanical testing machine. Then, a destructive axial rotation torsion test at a rotation rate of 1 degree/ second was conducted using an Enduratec materials testing machine. Boundary and loading conditions are applied to the FE model using NX software then exported to NASTRAN for assignment of elemental material properties [7]. Humeral torsional performance of five fixations constructs for completed pathological fractures are measured. Specimens are divided into five different constructs and tested in torsion. Forty adult left artificial humeri are used. Humeri are randomly assigned into five groups of eight specimens each and repaired using one of the construct systems from Zimmer. This method of fixation is likely to best to meet the goals of treatment of pathological fractures of the humerus by providing maximal initial stability, by protection of the entire length of the bone from weakening by subsequent metastases, and by avoiding the recognized complications associated with intramedullary nail fixation [3]. Nineteen subjects are investigated with flock of birds electromagnetic sensors attached to transcortical pins placed into the scapula and humerus, and a thermoplastic cuff secured on the arm. Humeral motion is recorded simultaneously from surface and bone fixed sensors. For all five motions tested, the plane of elevation rotation average absolute error ranged from 0^{o}-2^{o}, while the humeral elevation rotation average error ranged from 0^{o}- 4^{o}. The axial rotation average absolute errors are much greater, ranging from 5^{o} during elevation motions, to approaching 30^{o} at maximum excursion of internal/external rotation motions. Surface sensors are an accurate way of measuring humeral elevation rotations and plane of elevation rotations [9].

Conclusion

Only tentative conclusions can be drawn from the available evidence, which is insufficient to inform many of the decisions required in contemporary fracture management. Forces transmitted through the shoulder may reach up to 2.5 times of the BW during strenuous activities. Several biomechanical models of the upper extremities have been developed allowing the calculation of joint angles, joint forces and moments as well as the equivalent stress, strain and deformation values. It uses a finite element method to examine the mechanical parameters such as stress and strain at the interface between various implants and the humerus and scapula bones. The data collected from FEA showed the pattern of stress, strain and deformation of the bone at the interface that can be used to predict the failure of the bone material under load. This can help surgeons predict postoperative failures looking into the probability of loosening, notching, and bone inadaptability. The mechanical behavior of the Scapula and Humerus bones according to the effect of load transfer in the form of stress distribution which is based on the software analysis and experimentally validated realistic 3-D FE model can be studied.

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