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FEM model an effective tool to evaluate von mises stresses in shoulder joint and muscles for adduction and abduction.

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Abstract

Shoulder is one of the most complicated and critical joint. It consists of the clavicle, scapula and humerus. Studying individual functions of these structures is nearly unfeasible. In order to understand these relationships during different shoulder exercise, an attempt has been made to model, simulate and analyze the shoulder joint.

The technique described in this paper utilizes the advanced 3D scanning; Computer Aided Design (CAD), DMU Kinematics Tool in CATIA V5 then Finite Element Analysis (FEA) to detect the stress points of the shoulder joints during adduction and abduction. FEM of the ligaments and the muscles are carried out using the hexa-penta mesh elements in Hyper Mesh and von mises stresses are analysed by LS DYNA software. The results for abduction and adduction are plotted and validated with the previous research papers as well as the limiting values of the different shoulder muscle for the range of motion 0º to 30º.

1. Introduction:

Although the human body is an incredibly complex biological system composed of trillions of cells is subjected to the same fundamental laws of mechanics that govern simple metal or plastic structures. Biomechanics is also often referred to as the link between structure and function, Carol Oatis, (2009).

The shoulder is basically like a ball and socket**.** The "ball" is the head of the humerus and the "socket" is the glenoid part of the shoulder blade (scapula). The anatomy of the shoulder is unique - it has a relatively shallow socket which results in amazing flexibility and range of motion to the shoulder joint which is unparalleled elsewhere in the body. In order to achieve this flexibility but maintain a stable shoulder, there is a complex interplay between the joints, muscles and ligaments. Injury to any one of these structures can therefore result in significant ongoing pain, weakness, or

instability, Marieb EN et al. (2007), Terry GC et al.(2000),Martini FH (1998).

Therefore to study and evaluate the pain, which is associated with the stresses developed in these muscle and the joint, the proposed work is carried out. The present paper focuses on the shoulder anatomy, 3D scanning by an ATOS III scanner, CAD modelling by CATIA V5 and FEM analysis by Hyper mesh and LS DYNA software. By using this methodology stress analysis of the shoulder joint and muscle is carried out. The results are plotted by using a Von meses stresses for abduction and adduction. The stresses developed are plotted and concluded that maximum stresses developed are in Teres minor and Teres major muscles.
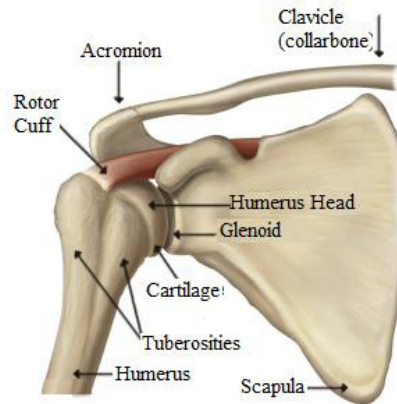

Fig.1. Shoulder joint bones (Courtesy Orthopedic surgery book)

2. Literature Review:

Though lot of work is in progress on the shoulder joint stress analysis and its behavior, still the exact stresses developed and its analysis is a big concern for the orthopedic surgeons. J Dul developed a simple two-dimensional biomechanical model of the shoulder to quantify shoulder muscle load, joint load and endurance time in work situations. The model is applicable to the analysis of working postures requiring elevated upper arm positions in the plane of the scapula, with the trunk upright, and the elbow flexed at 90º,J Dul (1988). *F.C.T. van der Helm* also developed a finite element musculoskeletal model of the shoulder. It is concluded that a detailed model of the shoulder mechanism has been developed which provides good insight into the function of morphological structures F.C.T. van der Helm (1994).This is the area in which work is to be progressed. *Daniel Kluess, Jan Wieding, Robert Souffrant et al.* developed FE-models of the implant-bone-compound and developed computed tomograms of biological structures for computational finite element-analysis and corresponding CAD-models of the implant Rho J Y et al. (1995),Snyder SM et al.(1991). They aimed at predicting the stress and strain states in the surrounding bone stock and in the implant itself and the potential to predict relative micro motion, Bergman GF et al. (1993). *Lionel THOLLON, Pierre-Jean ARNOUX, Frédéric MOURET, Christian BRUNET* developed a finite element model of the upper extremity to study the biomechanics of the shoulder in different configurations. They have reconstructed the geometry of the bones and articular structures of the shoulder from CT scan dataset, and meshed them via Hypermesh software. Then integrated the mechanical properties of each element with Radioss process. Three point bending tests on clavicle and humerus in static and dynamic conditions were performed along with simulation.

In present work the successful attempt is made to model a complex shoulder joint by using a 3D camera and then exporting the data in CATIA V5 for modeling. These shoulder parts are assembled and simulated in hyper mesh and the stress results were plotted for the range of motion 0° to 30°, of the shoulder joint movements for abduction and adduction. Previous to this shoulder joint movement for Flexion and Extension exercise stress analysis is done by the same author ,Shriniwas S Metan et al.(2013). These results were validated with the previous research papers as well as the limiting values of the different shoulder muscle stresses.
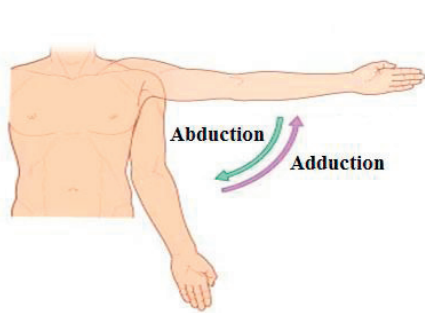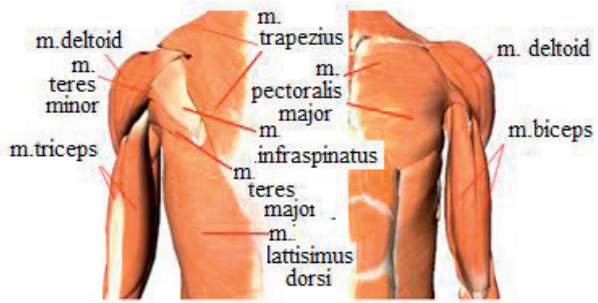
Fig.2. Shoulder joint exercise.   Fig.3. Shoulder muscles (Courtesy Google Body Browser)

3. 3d scanning and modeling of bones:

Geometrically accurate and anatomically correct 3D geometric models of human bones and implants are essential for successful preoperative planning in orthopaedic surgery. Such models are often used in various software systems for the preparation surgical interventions. Therefore, it is very important to create geometry of the bone rapidly and accurately,M.Viceconti (1998). Modelling of bones in CATIA without any background help is very difficult and impractical. The irregular shape of the scapula and humerus hampers the feasibility of the modelled profile.3D scanning of the bones to obtain a point-cloud was finalized to further our work on modelling,Fausto Bernardini et al.(2002). In the present work ATOS III 3D scanner is used for scanning the bones.

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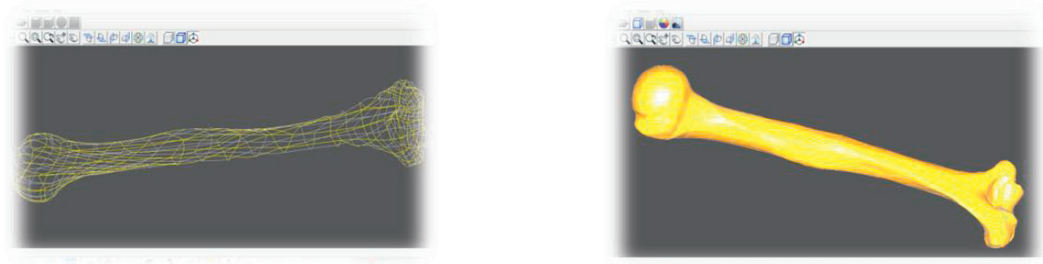Fig.4. Scanned model of Humerus and Scapula

Fig.5 STL file and scanned model of Humerus

After scanning the shoulder joint parts Humerus, Scapula and Clavicle, **.stl** files are generated and used further for modelling in CATIA.
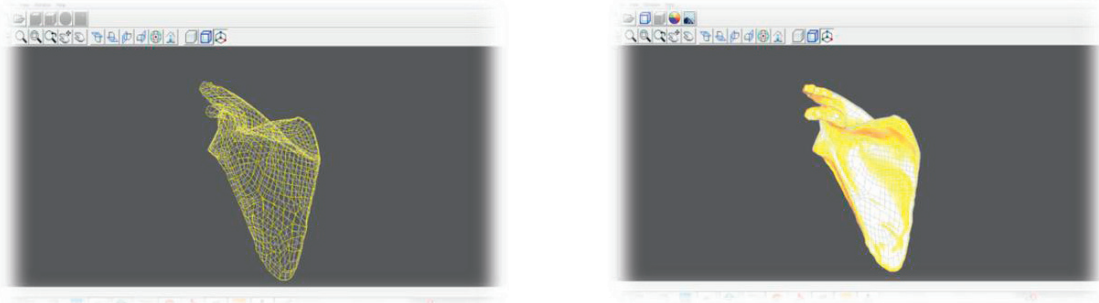
Fig.6. STL file and scanned model of Scapula

4. CAD Modeling :

Reverse modelling of a human bones geometry using CAD software means generating digital 3D model of bones geometry from 3D scanned model. In this particular case, CATIA V5 R19 CAD software and its modules were used. Importing the raw data into the CAD system results in generating of one or more clouds of points (discrete points of the bone, which are scanned by some of radiology methods). In the next phases of reverse modelling, the geometrical features of higher order (curves and surfaces) are designed. The process of creating model of humerus was based on the processes that are described in F C T van der Helm (1994), Melissa MB (2010).

5. Finite element analysis of shoulder joint:

The FEM method can simulate the deformations of complex systems that are otherwise difficult to assess and has been used to address a broad range of problems in the field of biomechanics and orthopaedics. Altair Hyper Mesh is a high-performance finite element pre-processo, that works with many finite element solvers is used in the present paper. User Manual Altair Hyperworks 10.0 (2012).

Fig.7 Modelling and Assembly of Shoulder joint   Fig.8 Simulation of Adduction and Abduction

The unique functionalities include extensive meshing and model control, morphing technology to update existing meshes to new design proposals and automatic mid-surface generation for complex designs with varying wall thickness. Solid geometry enhances tetra-meshing and hexa-meshing by reducing interactive modelling times, while batch meshing enables large scale meshing of parts with no manual cleanup and minimal user input. Moreover, Hyper Mesh has tools to clean up imported geometry containing surfaces with gaps, overlaps and misalignments that prevent high quality mesh generation.

Although Hyper mesh support different solvers, in the present application OptiStruct and LS-DYNA solvers are used for static analysis and dynamic analysis respectively to solve the present problem[12]. LS-DYNA is a general purpose explicit and implicit finite element program used to analyze the nonlinear dynamic response of three dimensional structures.User Manual Altair Hyperworks 10.0 (2012). Its fully automated contact analysis capability and error checking features have enabled users worldwide to solve successfully many complex crash and forming problems. Hyper View combines advanced animation and XY plotting features with window synchronization to enhance results visualization.

5.1 3D Modelling:

Processing the Shoulder Joint assembled model in HYPERMESH required importing the same in IGES format. Then Clean up tool was used for the missing data such as some edges, corners etc and with the help of shell element the modelling of different muscles and ligaments is carried out in design workbench of HYPERMESH.

The muscles and ligaments surfaces are created with integration of Hexa-Penta mesh in HYPERMESH. For the simulation and analysis of shoulder joint, it is desirable to use a mesh of hexahedral and pentahedral elements due to change in thickness at different points of ligaments and muscle.

5.2 Material properties:

The cortical bone humerus is simulated with respect to muscles, ligaments and two bones scapula and clavicle. Therefore, the humerus bone is considered as rigid element, while the other bones scapula, clavicle and Muscles, Ligaments as elastic material. In order to analyze the model in actual condition certain geometrical and material properties has to be applied to the model. Based on these properties it will deform or change it shape and thereby
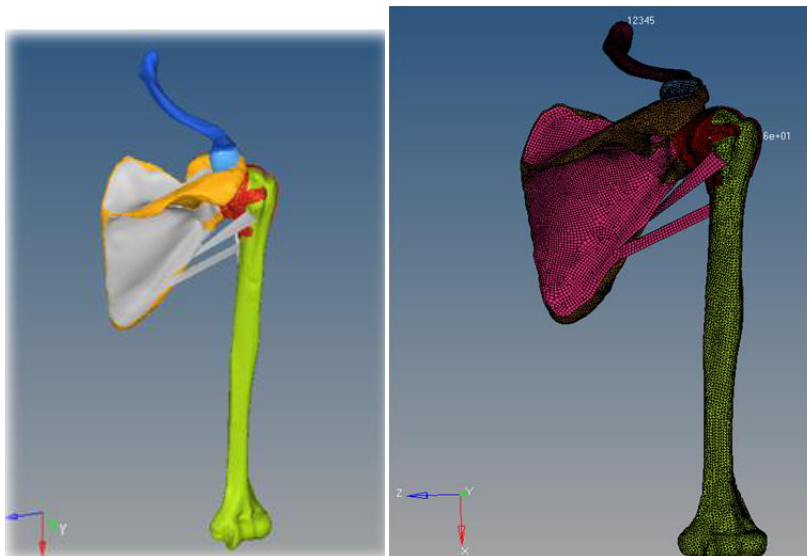

Fig. 9. HYPERMESH view of Shoulder Model**.**

Table 1. Material Properties of Muscles and Ligaments. Novotny, J.E et al.(2000), S.S. Metan et al.(20130),M Viceconti (1998).

Muscles	Eo (MPa)	Poisson Ratio	Ligaments	Thickness (mm)	Poisson Ratio
Infraspinatus	1.2	0.45	Glenohumerul	2.5	27
Subscapularis	1.2	0.45	Conoid	0.98	25
Deltoid and Triceps	0.5	0.45	Trapezoid	0.98	25

Table 2. Material Properties of Bones. Novotny, J.E et al.(2000).

Bones	Poisson Ratio	Yield Stress MPa	Density Kg/m^3	Young's Modulus MPa
Cancellous Bone	0.3	7.7	1000	1100
Cancellous Bone	0.3	7.7	1000	1100

5.3   Meshing:

Meshing of the model was done after the material collectors and assigning each collectors to each of the component. Tetra elements were used for meshing the bones with element size of 2mm. Tetra elements better approximate the shape with minimal errors as compared to brick elements Ligaments and Muscles are meshed with Hexa and Penta elements with the element size of 2mm. After meshing the elements generated for bones is shown in table below. The elements generated for Humerus Clavicle and Scapula are 57921, 9887, 49484 respectively.

Type 7 interface contact available in HYPERMESH is used to define interface contact. Characteristics of this contact are that impacts occur between a master surface and a set of slave nodes and also a node can impact on multiple segments on either side of the master surface, B.Ravi and R Ghavar (2008).
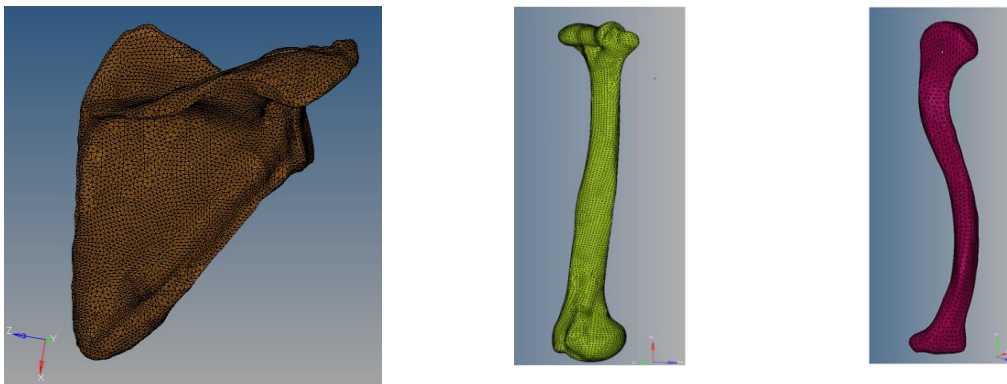

Fig.10.   Meshed model of Clavicle, Humerus and Scapula.

6. Results:

The solved model file is exported to HYPERVIEW for post-processing. In HYPERVIEW, the model can be viewed in various forms and judged by different parameters. In this case two major parameters are Von Mises stress and displacement of the components. The boundary conditions are defined in LS DYNA. The farther end of the Clavicle is fixed so that the other end of the Clavicle which joins the Humerus and the Scapula is in relative motion. No external load is applied as the self weight of the arm acting on the joint between Humerus and Scapula is considered for adduction and abduction exercises.

The bone, muscle and ligament weight is also taken into consideration. The angular velocity applied on the free end of Humerus is 10 mm/s. As it is dynamic analysis, the Von Mises stresses acting on these bones vary according to the rotation (time). The stresses and displacement charts are plotted for adduction and abduction. The numerical method used for finite element analysis of the joint is Forward Difference Method. The following figures and tables describe the various stresses acting on the ligaments, muscles and bones of the shoulder joint.

From the above table, the stresses obtained after the simulation of shoulder joint vary for various parts Glenohumeral joint. Maximum stress is obtained at the Teres Minor while the least stress is obtained at the long head of Triceps. The stress at the Subscapularis muscle is 0.685 MP. These are within the allowable muscle stresses.
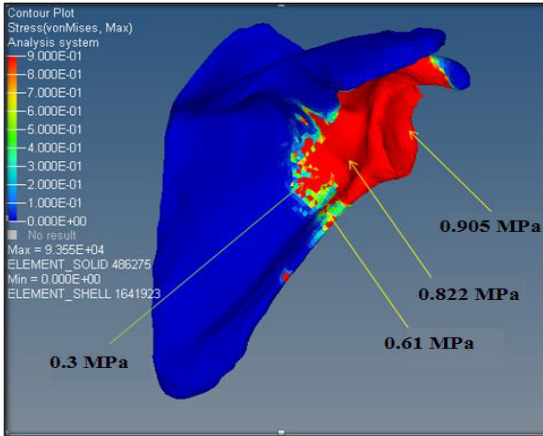
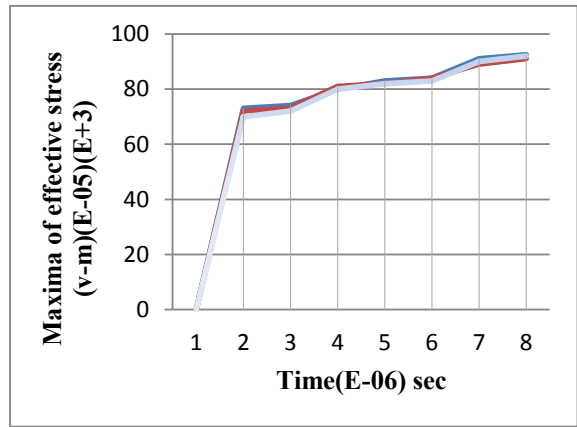Fig.11. Stresses induced due to stretching of muscles during adduction.
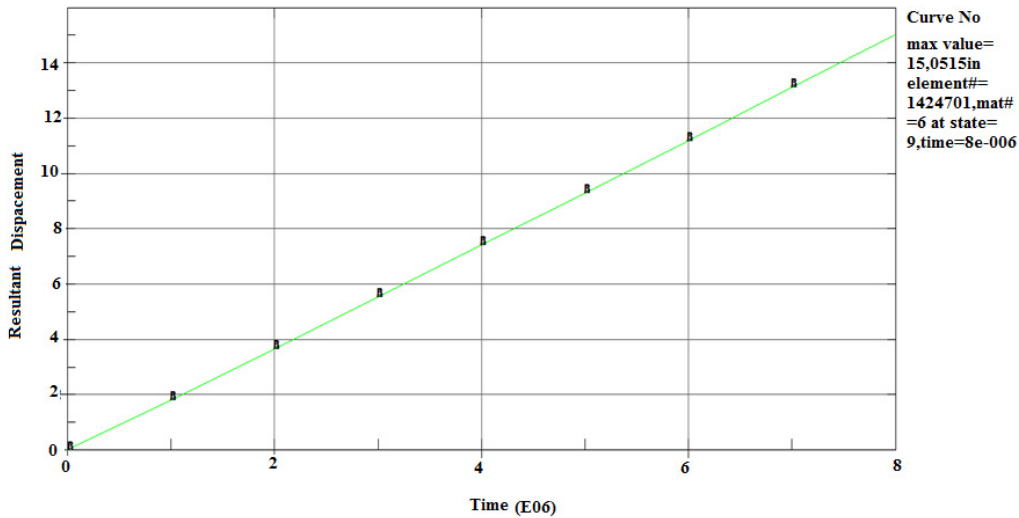

Fig.12. Maxima of effective stresses w.r.t.time.

Fig.13. Displacement of Humerus with respect to time.

Table 3. Stresses near the Glenohumeral Joint and costal muscles.

Ligament / Muscle	Stress MPa	Ligament / Muscle	Stress MPa
Teres Minor	0.925	Teres Major	0.90
Subscapularis	0.685	Coracobrachialis	0.42
Long head of Triceps	0.10	Subscapularis	0.115

Sanjay Gupta and Prosenit Dan (2004). From the above table, the stresses obtained after the simulation of shoulder joint vary for various parts on the costal muscles. Maximum stress is obtained at the Teres Major while the least stress is obtained at the Subscapularis muscle. The stress at the Coracobrachialis muscle is 0.42MPa. These are within the allowable muscle stresses, Sanjay Gupta and Prosenit Dan (2004), Sung-Woo Koh et al (2005).

As we can observe, the stresses obtained after the simulation of shoulder joint vary for various parts on the dorsal muscles. Maximum stress is obtained at the Teres Minor muscle while the least stress is obtained at the Subscapularis muscle. The stress at the Infraspinatus muscle is 0.42MPa.

As it is observed that the stresses obtained after the simulation of shoulder joint vary for Labrum and the muscular section between Humerus and Scapula. Maximum stress is obtained at the Glenohumeral Labrum muscle while the least stress is obtained at the Subscapularis muscle. The stress at the Infraspinatus and Supraspinatus muscles is 0.705 MPa. It can be seen that the stresses on the muscles and ligaments go on reducing as they go further away from the Labrum / ball and socket joint.
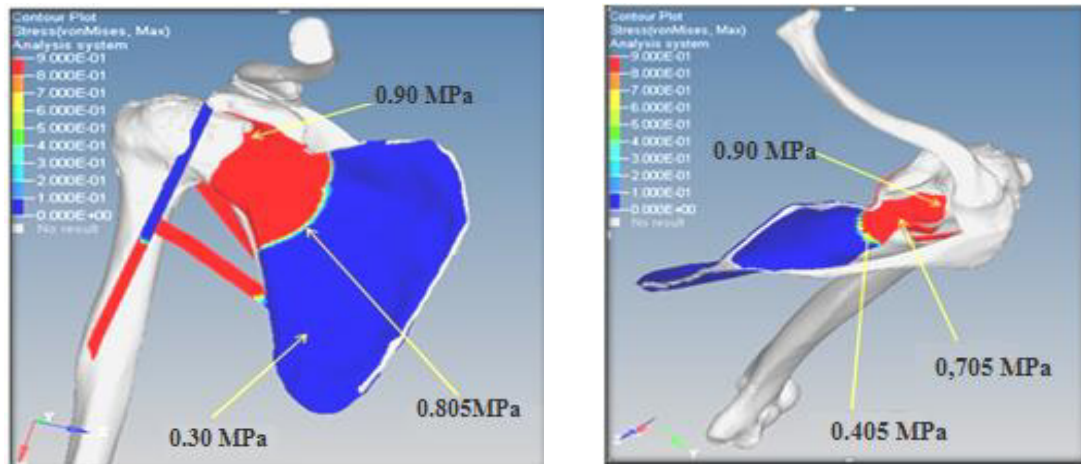

Fig.14. Von Misses Stresses on the dorsal muscles.

Table 4.   Von Misses Stresses on Labrum and the muscular section between Humerus and Scapula and Von Misses Stresses on the costal muscles and on Labrum:

Name of Ligament	Stress MPa	Name of Ligament	Stress MPa
Labrum	0.90	Teres Minor	0.925
Supraspinatus,Infraspinatus	0.705	Infraspinatus	0.39
Subscapularies	0,405	Supraspinatus	0.22

7. Discussion:

The basic aim of this study was to evaluate the Von Mises stresses generated on Glenohumeral Joint, costal muscles and dorsal muscles during adduction and abduction shoulder exercise. The shoulder is basically like a ball and socket joint. The irregular shape of the scapula and humerus hampers the feasibility of the modeled profile therefore modeling of bones in CATIA without any background help is very difficult and impractical. The range of motion for this analysis is carried out for 0 to 30 degrees owing to long time in iterations and numerous approximations. This work can be extended by increasing the movement of the adduction and abduction movements' up to 150 degrees. More detailed analysis of other shoulder movements such as Flexion, Extension, External Rotation, Internal rotation can be carried out. Analysis of more complicated movements such as the combination of these movements can be carried out.

8. Conclusion:

Successful attempt has been made to model, simulate and analyze the shoulder joint. No compromise was made regarding the accuracy during the modelling of the bone. The analysis of the shoulder joint was performed by using high end analysis software such as LS DYNA and HYPERMESH. Thus an attempt has been made to achieve accurate results keeping in mind the various research applications this project can have.
The study was to analyze the various bones, ligaments and muscles which together form the shoulder joint, use 3D

scanners and advanced modelling packages for accurate modelling and drafting of the bones and finally performing simulation and kinematic analysis of shoulder joint so as to obtain stress and displacements of different muscles and bones in the shoulder joint.

Present study demonstrates how much degree of rotation should be given to the shoulder joint to restrain the amount of stresses occurring in the shoulder joint. The scope of the project can further be enhanced by assembling the further bones of human arm, radius and ulna. More detailed analysis of other shoulder movements such as internal rotation, external rotation, Flexion and Elevation for normal Range of Motion can be carried out.

9. Acknowledgements:

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