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Sensitivity analysis of shoulder joint muscles by using the FEM model

Shriniwas. S. Metan[*1], G.C. Mohankumar[2a] and Prasad Krishna[2b]

[1]*Department of Mechanical Engineering, NK Orchid College of Engineering & Technology, Solapur, Solapur, India.*
[2]*Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal Karnataka, India*

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Abstract. Shoulder pain, injury and discomfort are public health and economic issues world-wide. The function of these joints and the stresses developed during their movement is a major concern to the orthopedic surgeon to study precisely the injury mechanisms and thereby analyze the post-operative progress of the injury. Shoulder is one of the most critical joints in the human anatomy with maximum degrees of freedom. It mainly consists of the clavicle, scapula and humerus; the articulations linking them; and the muscles that move them. In order to understand the behavior of individual muscle during abduction arm movement, an attempt has been made to analyze the stresses developed in the shoulder muscles during abduction arm movement during the full range of motion by using the 3D FEM model. 3D scanning (ATOS III scanner) is used for the 3D shoulder joint cad model generation in CATIA V5. Muscles are added and then exported to the ANSYS APDL solver for stress analysis. Sensitivity Analysis is done for stress and strain behavior amongst different shoulder muscles; deltoid, supraspinatus, teres minor, infraspinatus, and subscapularies during adduction arm movement. During the individual deltoid muscle analysis, the von Mises stresses induced in deltoid muscle was maximum (4.2175 MPa) and in group muscle analysis it was (2.4127MPa) compared to other individual four rotor cuff muscles. The study confirmed that deltoid muscle is more sensitive muscle for the abduction arm movement during individual and group muscle analysis. The present work provides in depth information to the researchers and orthopedicians for the better understanding about the shoulder mechanism and the most stressed muscle during the abduction arm movement at different ROM. So during rehabilitation, the orthopedicians should focus on strengthening the deltoid muscles at earliest.

Keywords: shoulder joint; deltoid; supraspinatus; von Mises stresses; abduction; equivalent elastic strain

1. Introduction

[*]Corresponding author, Ph.D., E-mail: shrinims@gmail.com
[a]Ph.D., E-mail: mkumargc@gmail.com
[b]Ph.D., E-mail: krishnprasad@gmail.com

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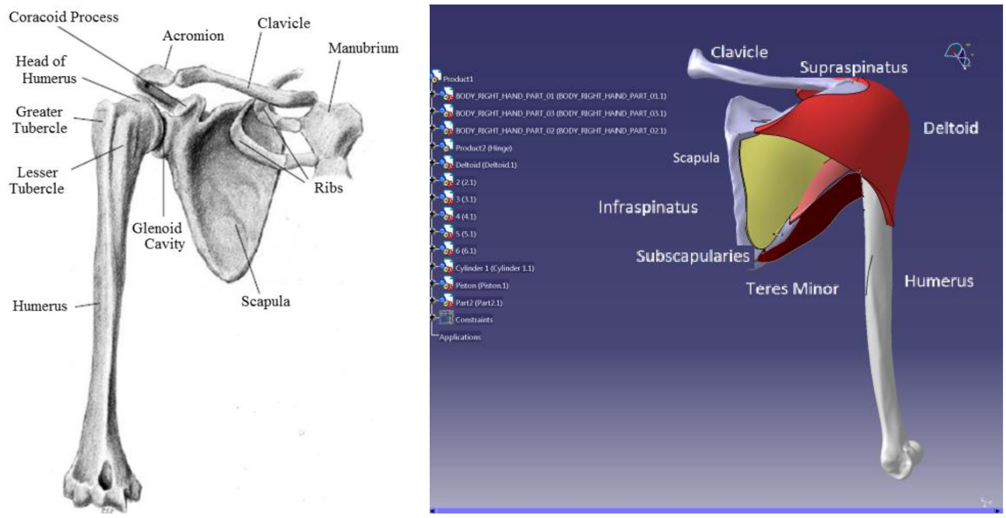


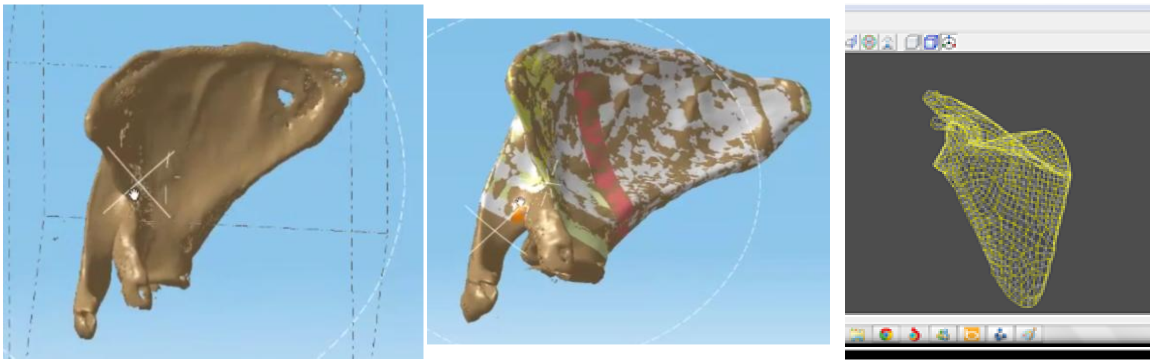
Fig. 1 Shoulder Joint Anatomy and 3D model with bones and five major muscles. (Romanes 2012)

The shoulder complex is the functional unit that results in the movement of the arm with respect to trunk. It mainly consists of clavicle, scapula, humerus and different muscles as shown in Fig.1. Shoulder muscles are the complex fibrous structure surrounded by different tissues and blood vanes. In order to analyse the behaviour of shoulder joint, a numerical model should consider the precise bones, its geometry and the various muscles which stabilize the shoulder joint.

Different numerical models for investigating complex shoulder joints were proposed. Computational models can be used to determine the cause and effect relationships. FEM models give an opportunity to calculate parameters which are difficult, or impossible to obtain experimentally. One classic example of this is the difficulty of measuring muscle force in vivo under dynamic conditions. To determine the muscular forces, a model based on the inverse dynamic theories was used (Karlsson *et al*., 1992; van der Helm, 1994; Hughes *et al*. 1996).

To determine the stress distribution within individual bones, model based on deformable body concept was used (Barbara *et al*. 1998; Friedman *et al*. 1992; Lacroix *et al*. 1997; Orr *et al*. 1988; Stone *et al*. 1999). Recent shoulder models have represented muscle geometry as a collection of segments, which does not give precise results. As the muscle attachment to the bones; muscle to muscle interaction, fibre arrangement and shoulder axis of rotation are not considered. To determine muscular forces and stresses, model with inverse dynamic theory with finite element models were used (Murphy *et al*. 2001; Lacroix *et al*. 2000). To analyze the stresses developed in the shoulder muscles during the working postures for elevated upper arm position, a two dimensional model was developed (Dul 1988). The entire musculoskeletal mathematical model was developed to analyze the muscle behavior during upper arm movement (Garner *et al.* 2001).

Force analysis of a Biomechanical musculoskeletal model of the upper extremity including 15 degree of rotation and 50 muscles was done (Holzbaur *et al*. 2005). A real-time, three-dimensional, musculoskeletal model to analyse dynamic behaviour of human shoulder and elbow was developed. This 3D model of upper limb provides real time feedback of the arm motion which allows performing experiments on the patients in a closed loop during elevation arm movement (Edward *et al*. 2009). A 3D CT scan dataset of the different bones of human anatomy were meshed in hyper mesh and after adding mechanical properties to them with radios. The static and dynamic



(a) Scapula scanning with ATOS III (b) Thinning and shape cleaning (c) stl file generation

Fig. 2 Scanning stages to form .stl file to export in CATIA V5 model generation

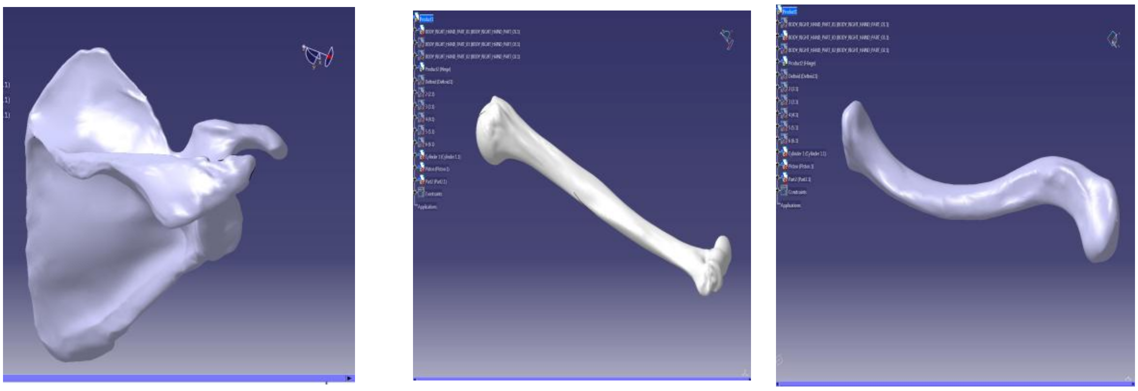
conditions were performed along with the simulation (Lionel *et al*. 2007). To overcome these issues, a 3D shoulder model with five major rotor cuff muscles was developed. The present work is the first detailed 3D finite element model with five major rotor cuff muscles of a shoulder joint for analysing the von Mises stresses distribution during abduction. Previous to this study shoulder stress analysis for the flexion and extension arm movement is done by the same author, (Metan *et al*. 2014). The Sensitivity analysis is done for von Mises stresses during abduction for different rotor cuff muscles and shoulder muscle for the maximum range of motion (ROM). The kinematics for shoulder abduction was prescribed as input to the finite element simulations and the resulting muscle stresses were predicted.

2. Methods

The shoulder joint is one of the complex joint having maximum degrees of freedom. Its stability and controlled movement are one of the major concerns for the orthopedic surgeons. Accurate topology of all the shoulder bones and muscles is a key to create a valid and accurate 3D shoulder model which will be effective in preoperative planning for the Orthopedic Surgeon. Therefore, it is logical to base process of geometrical modeling of shoulder on its anatomical and morphological properties (Marko *et al*. 2011).

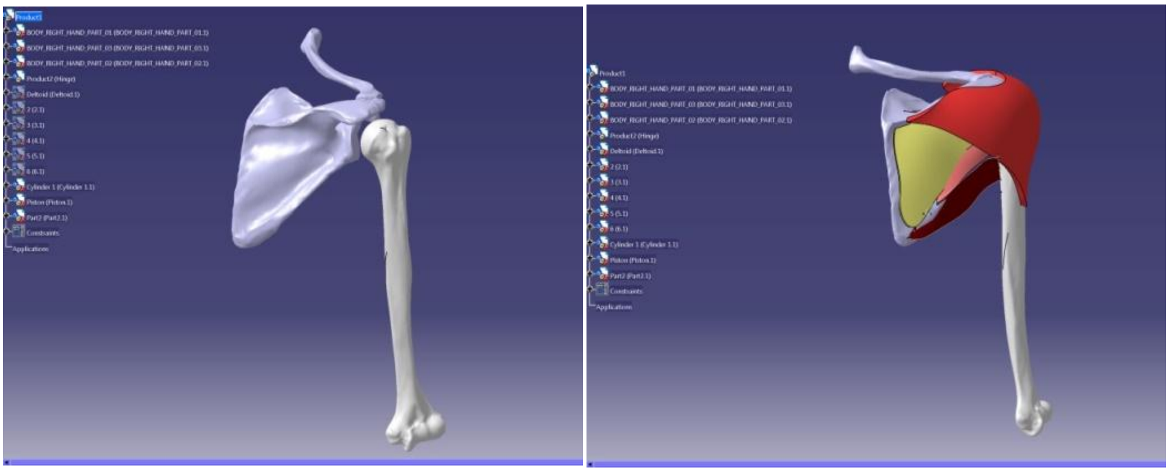
2.1 Scanning of the shoulder bones:

Reverse modeling is the one of the fast and accurate option to reproduce a complicated 3D objects such as shoulder bones. By using 3D scanning (ATOS III scanner) three shoulder bones scapula, humerus and clavicle images with the required accuracy and detailed contours were created (Fig. 2). The scanned object is then imported into geomagic studio and all points outside the relief area were deleted and various scans were merged into single data. Thinning of the object was done to reduce total number of points by deleting surplus points in repeatedly scanned areas. Meshing was done to create about 8 million triangles in case of Humerus. To generate an accurate and detailed model shape-cleaning algorithm was used. Finally .stl file was generated.



(a) Scapula (b) Humerus (c) clavicle

Fig. 3 Shoulder bones developed in CATIA V5 model



(a) Shoulder model with precise orientation and gap between Humerus, Scapula and Clavicle.

(b) Shoulder model Assembly with five major shoulder muscles.

Fig. 4 Glenohumeral model with bones and five major muscles.

2.2 CAD Modeling

3D models of bones geometry from scanned .stl file was done in CATIA V5 R19 software. The geometrical features of higher order (curve and surfaces) were designed by filtering and aligning number of cloud points, tessellation of polygonal model, recognition and defining the referential geometrical entities. Complicated contoured 3D model of humerus was created by generating anatomical points and spline curves. Similarly clavicle and humerus 3D models were designed and detailed contouring was done. The mechanical properties of these bones region depend upon the square of the apparent density. According to quadratic dependency, a non-homogeneous bone constitutive law was developed and implemented (Terrier *et al*. 1997; Rakotomanana *et al*. 1999).

Assembly of Humerus, Clavicle and Scapula in pre-defined direction and coordinates was carried out in Assembly Design Workbench of CATIA V5. Different muscles were added. It was then imported in .igs format into ANSYS workbench and was refined with surface merging in

Table 1 Description of the constitutive laws and mechanical properties used in the model (Hayes 1991; Reilly *et al*. 1974; Novotny 2000; Rice JC 1998)

Element	Type of laws	Poisson's Ratio	Young's Modulus	Density
Bone	Linear Elastic ,non-homogeneous	0.3	15000 MPa	1800Kg/m^3
Muscles	nonlinear hyper elastic laws, incompressible	0.45	1.2 MPa	1000Kg/m^3

ANSYS. The model was then exported to ANSYS for stress analysis. The model comprises three dimensional shoulder geometry including three major bones and five different rotor cuff muscles.

A non-homogeneous constitutive law was used for bones as well as nonlinear hyper elastic laws are used for rotor cuff muscles and for cartilage. Muscles were considered as active structure. Glenohumeral contacts and bone muscle contact were modeled with discontinuous unilateral large sliding laws. The normal laws were based on the exponential function. The law allows some penetrations of the slave surface and considers a contact force with positive contact distance.

These considerations provided a good numerical stability (Joshua *et al*. 2014). Careful alignment of the five muscles on humerus, scapula and clavicle are done and also the initialization and location of those were done accurately (Blemker *et al*. 2005) (Delp *et al*. 2005).

Total 58 surfaces were added in humerus to deltoid connection, 28 surfaces in scapula to deltoid and 32 surfaces in clavicle to deltoid. Maximum contact between deltoid to shoulder joints was taken in the modeling design. The importance of the gap between shoulder joints and axis locations, during abduction were precisely done in the shoulder CAD model. The von Mises stresses, equivalent elastic strains were analyzed for abduction arm movement for full range of motion. The kinematics for shoulder abduction was prescribed as input to finite element simulations and the resulting muscles stresses were predicted.

3. Material properties

The efficacy of the results obtained in any analysis depends upon its material properties. Sample of all the muscle tissue with various length and thicknesses was used. For deltoid thickness of the muscle is taken as 10mm and the remaining muscles 5mm (Kim *et al*. 2007). A non-homogeneous constitutive law was used for bones as well as nonlinear hyper elastic laws were used for rotor cuff muscles and for cartilage. Muscles were considered as active structure (Joshua *et al*. 2014). The muscle element with refined mapped mesh with element size 3mm was used for the analysis.

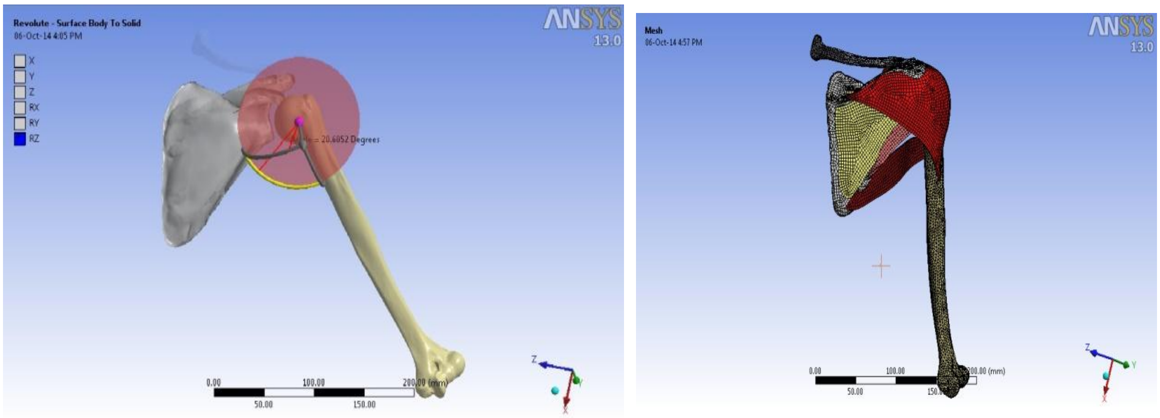
3.1 Loading condition

The efficacy of the Glenohumeral joints model i.e. humerus, clavicle, scapula depends on the positioning, orientation and maintaining proper gap amongst the three bones during abduction (Van der Helm FC, 1994). The shoulder bone orientation and alignment was done with utmost care and each bones axis and gap between them is maintained (Romanes 1986).

The axis of rotation of humerus was tested against the interference with scapula and clavicle for abduction arm movement. 3D muscle models requires more input data than line segment models

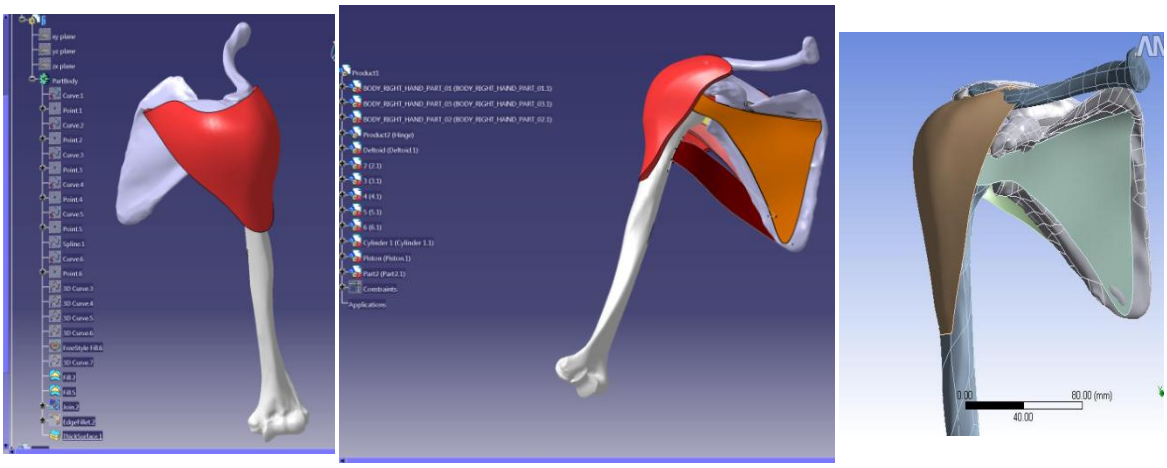
Table 2 Summary of total nodes and elements in the finite element model Analysis

Muscle	**Nodes**	**Elements**
Deltoid	33676	23663
Infraspinatus	33167	23115
Subscapularies	33068	23051
Teres minor	32517	22527
Supraspinatus	33392	23363



(a) Shoulder joint rotation from 0° to 80° (b) Meshing of shoulder muscle in ANSYS.

Fig. 5 Simulation and meshing of shoulder joint in ANSYS.



(a) Deltoid muscle (b) All five rotor cuff muscles (c) Simulation

Fig. 6 Different muscles added in CATIA V5 during 3D models simulation in ANSYS

also contact and wrapping of the muscle plays an important role in analyzing its behavior in deformation. Each muscles architecture, its origin and insertion was done taking in to consideration about its structural design (Joshua *et al*. 2012).

First Deltoid muscle was added to the shoulder bones and the von Mises stresses and equivalent

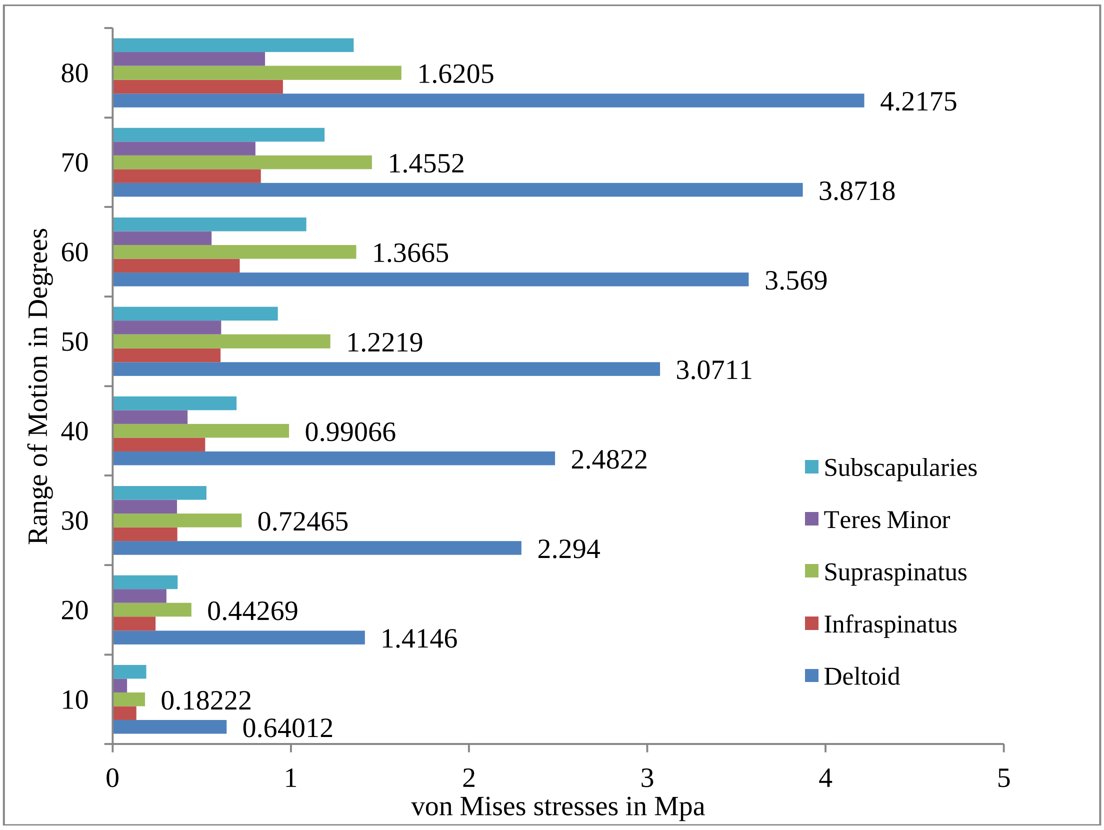


Fig. 7 von Mises stresses distribution during individual muscle analysis for abduction arm movement

elastic strain were computed for full range of motion in abduction. The neutral position was taken at vertical downward direction and then humerus along with the muscle was rotated from 0° to 80° in the interval of 10°.

The simulation was done in eight steps in eight seconds and each second corresponds to 10° rotations, the motion was chosen to be pure rotation. Probes were added at five different points in the muscle and the maximum stress was considered in the analysis. Similarly different four rotor cuff muscles were added individually and the same procedure was adopted to analyze stress behavior. Then after adding all the five muscles on the shoulder model the analysis was done and the stresses induced were tabulated. The kinematics for shoulder abduction and adduction rotation was prescribed as input to finite element simulation, and the resulting muscle stresses and strains were predicted.

4. Results

After modeling the shoulder with five major muscles in CATIA V5, it was then exported to ANSYS and boundary conditions were applied. The farther end of the clavicle was fixed and the relative motion is given to humerus along with all the muscles. No external weight was added to the model, as self-weight of the arm is 5% of the body weight; it was added during the 3D model

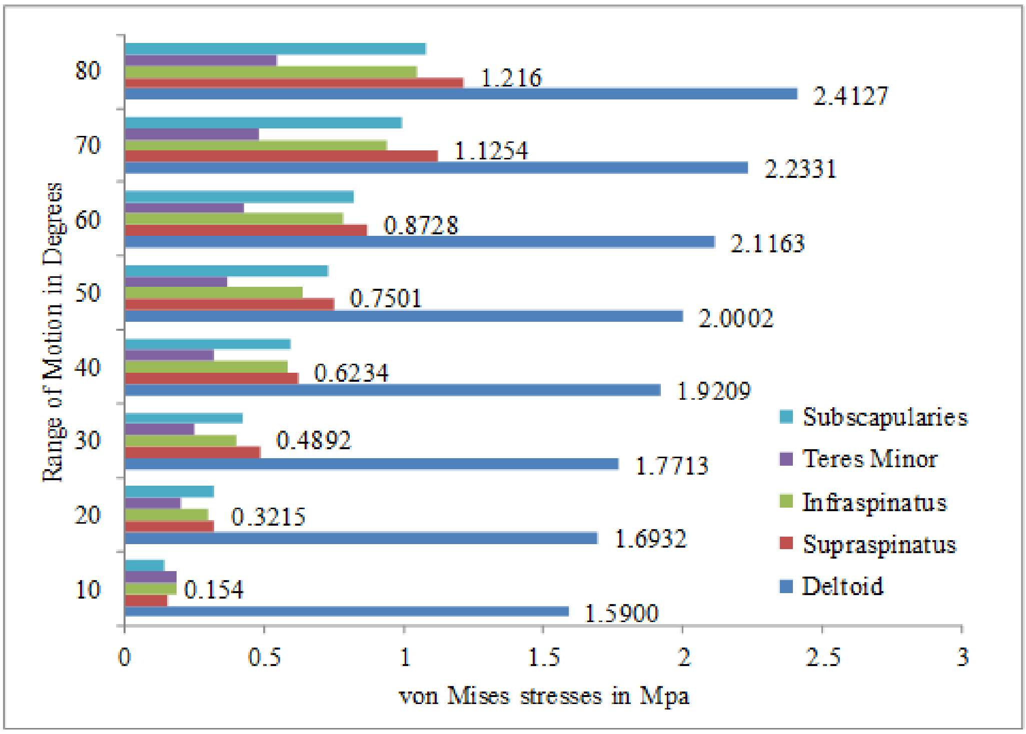
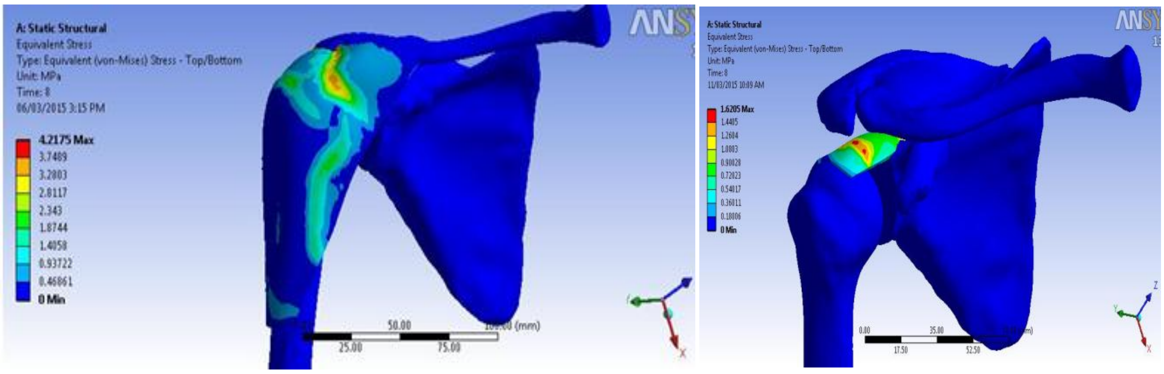


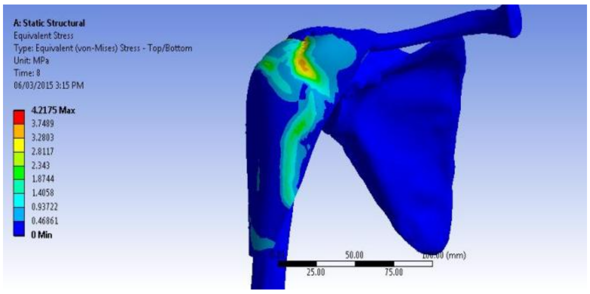
Fig. 8 von Mises stresses distribution during group muscle analysis for abduction arm movement



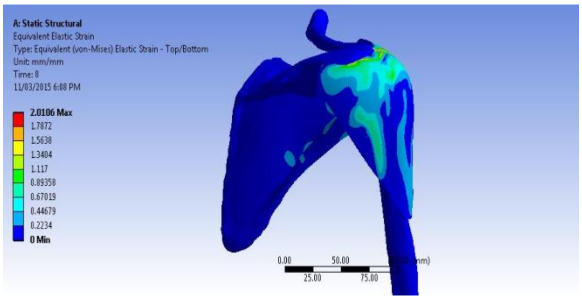
(a) deltoid (b) supraspinatus

Fig. 9 von Mises stress distribution for individual muscle analysis

simulation. Fig.7 shows the behavior of different muscles when added individually on the model and then analyzed for abduction from 0° to 80° in ANSYS APDL solver. Deltoid muscle was one of the most sensitive muscles for abduction, after supraspinatus and then rest of the muscles. Dul with the mathematical model observed the same that the maximum force were induced in deltoid and supraspinatus in case of abduction at 85° (Kim *et al*. 2007). The 3D model analysis was done by Webb agrees the same trend of the muscle behavior during abduction (Joshua *et al*. 2014). The analysis was done for the displacement of the muscles during abduction, in which deltoid and

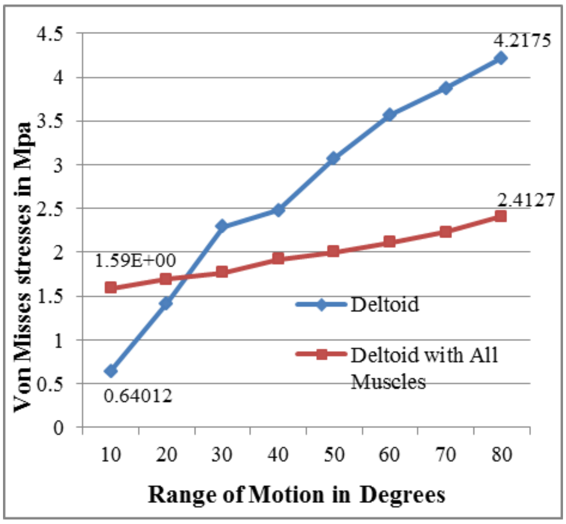


(a) single deltoid muscle added

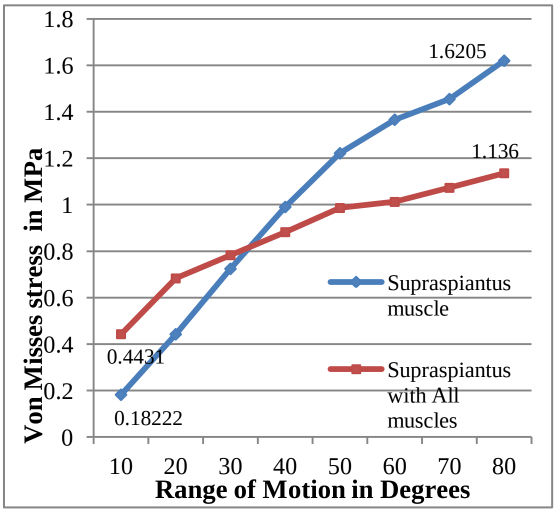


(b) deltoid muscles along with four muscles added

Fig. 10 von Misses stresses induced in the deltoid muscle.



(a) single deltoid muscle and deltoid with all four muscles added



(b) single supraspinatus muscle and supraspinatus with all four muscles added

Fig. 11 Equivalent stresses induced during abduction and adduction on muscles

supraspinatus are the two major muscles having maximum deflection.

In the group analysis when all the five muscles were added to the shoulder model, the deltoid muscle had shown a stress variation from 1.59MPa to 2.4127MPa for 10°to 80° during abduction arm movement (Fig. 8). In case of individual muscle analysis of the deltoid muscle, for the same degree of rotation the stress variation was from 0.64012MPa to 4.2175MPa (Fig. 7). So the deltoid muscle was the most sensitive muscle in both the analysis during abduction arm movement.

In the group analysis when all the five muscles were added to the shoulder model, the supraspinatus muscle had shown a stress variation from 0.4431MPa to 1.136MPa for 10°to 80° range of motion during abduction arm movement. In case of individual muscle analysis of the supraspinatus muscle, for the same degree of rotation the stress variation was from 0.64012MPa to 4.2175MPa. So the supraspinatus muscle was the sensitive muscle in both the analysis during abduction arm movement after deltoid muscle.

The same trend was found during the exercise conducted on the patients using Electromyography (EMG) machine. The graph of the Amplitude Vs. number of motor units was

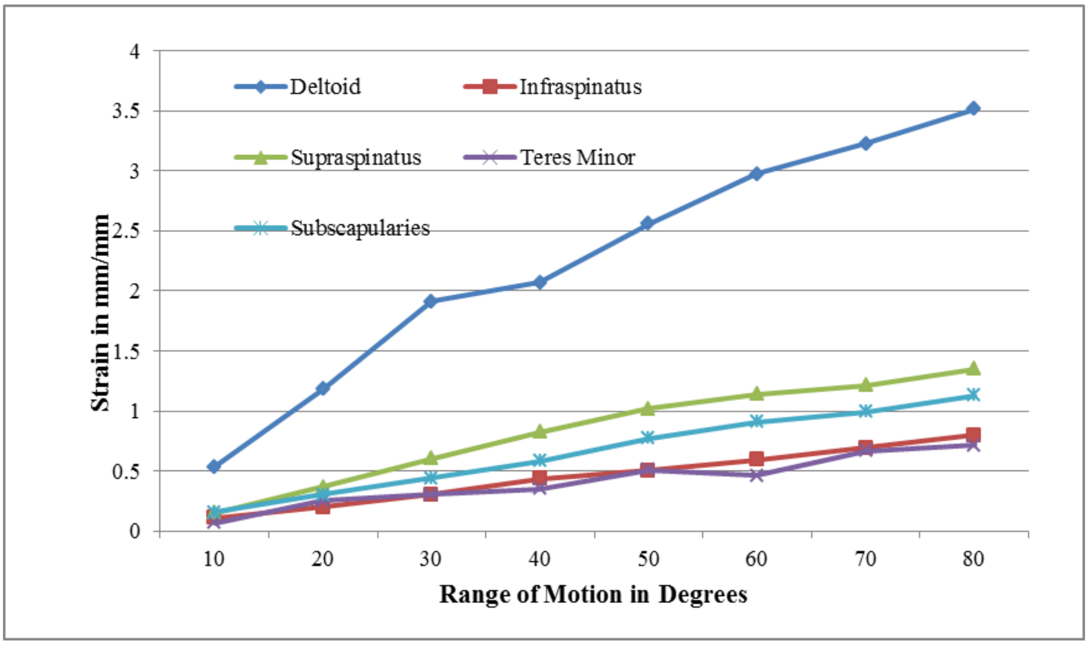


Fig. 12 Equivalent elastic strain induced during abduction arm movement

observed for five different muscles. The number of firing points of the motor unit was observed in the deltoid muscle and then on supraspinatus muscle. It also shows that the maximum firing points were in the range of 80° to 90° of ROM.

Fig. 10 shows the von Mises stress distribution in all the muscles in individual muscle analysis and in a group muscle analysis on the 3D shoulder model during abduction arm movement. Deltoid was the key to be focused in case of injuries or after post-operative treatment for abduction movement of the patients. Doctors can enhance the strength of the muscles with different treatments.

Due to stress distribution amongst all the muscles the load on deltoid muscle has been reduced by 42.8% and supraspinatus muscle by 30%. So each muscle was important and should be taken care during the shoulder movement.

The equivalent elastic strain for different muscles was also analyzed for abduction. The deformation per unit length also shows the trend that deltoid muscle had more deformation than the rest muscles.

5. Discussion

The purpose of this study was to analyze the stresses induced in different shoulder joint muscles during abduction arm movement by using FEM model. Also to study the sensitivity analysis of the shoulder muscles stress during abduction arm movement. A lot of work has already been done on the behavior of shoulder joint muscles for different gestures, for shoulder force analysis and Glenohumeral joint analysis, but the present model differs from other models in the following aspects.

The efficacy of the Glenohumeral joints i.e. humerus, clavicle, scapula positioning, orientation and gap maintained amongst these three bones for abduction (Romanes 1986). There was no clash between shoulder bone to bone, muscle to muscle and muscle to bone during FEM analysis for the full range of motion.

The orientation and muscle attachment to the shoulder bones plays a vital role in the shoulder rotation and its stability. The muscle thickness varied from 5mm to 10mm along with its length to create a proper volume of tissue over the shoulder bones. This ensured the real time behavior of the shoulder joint with the animated one.

Sensitivity analysis was done first time amongst the five shoulder joint muscles during abduction arm movement. Behavior of individual muscle during abduction for von Mises stresses and equivalent strain behavior were analyzed and also its behavior after adding all the muscles on the shoulder joint was discussed at length.

As for all numerical models, applying the boundary conditions is a difficult task. In case of shoulder which was the most critical joint in human body, model including all the five muscles along with its stability and consistency with respect to normal ROM was also a difficult task. For this reason, in the present work the boundary conditions were chosen to reproduce pure rotations.

The von-Mises stress behavior produced by this FEM model had strong correlations with the actual EMG test done on the patients on the developed shoulder CPM machine.

During the SEMG muscle analysis, the muscle contraction (stress) obtained in deltoid muscle was maximum (325 μV; 300 μV and 200 μV) compared to other four rotor cuff muscles at different ROM during the abduction arm movement.

The present work results are in agreement with the work done by Dul *et al*. (1987), Holzbaur *et al*. (2005), William *et al*. (2010) and Webb *et al*. (2014); the deltoid muscle is the most sensitive muscle during the abduction arm movement.

The purpose of this study was is to give researchers and orthopedicians a better understanding about the shoulder joint mechanism and the most stressed muscle during the abduction arm movement at different ROM.

6. Conclusion

A successful attempt has been made to find out the sensitivity analysis for stresses and strain, of the shoulder joint muscle during abduction arm movement. The detailed shoulder model was scanned, modeled in CATIA V5 work bench and then analyzed for the stress behavior in the shoulder rotor cuff muscles and deltoid muscles. Results obtained with the 3D model were in agreement with clinical observations and also work done by by Dul (1987), Holzbaur *et al*. (2005), William *et al*. (2010) and Webb *et al*. (2014). The study was done for both individual muscle analysis and group muscle analysis. The study showed that deltoid muscle was the most sensitive muscle with the von Mises stresses 4.2175 MPa in individual and 2.4127 MPa in the group analysis for during abduction arm movement. So during rehabilitation, the focus of the orthopedic surgeon should be on strengthening the deltoid muscle at earliest by using different therapies. The maximum stress induced was during 70° to 80° of shoulder arm rotation which was in agreement with J Dul, (1988). This model can further be used for elevation and extension exercise behavior with little modification in the orientation of shoulder joint. The stress values and the trend of stress distribution will help the Orthopedic Surgeon to take corrective measures to expedite the shoulder healing process.

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