Finite Element Analysis of Reverse Shoulder Joint Prosthesis

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ABSTRACT

Rotator cuff tear is one of the most common cases among patients that cause severe pain and reduced performance in shoulder joint. Recently, in order to relieve pain and restore stability and function of shoulder, shoulder replacement is commonly performed. However, when normal shoulder replacement is not sufficient to restore the joint function, the reverse shoulder replacement is performed. In reverse replacement unlike the traditional replacement system, which is same to the normal shoulders, the ball component is positioned to the glenoid and the socket is placed to the proximal humerus. Reason of this altered anatomy is to provide a greater lever arm for the deltoid muscle to regain active shoulder elevation. Some complications after reverse shoulder replacement such as loosening in glenohumeral joint and failure of prosthesis at the glenoid attachment area have been reported.

Aim of this thesis is to recognize the probable failures at the glenoid prosthesis and artificial glenohumeral joint. In this thesis a 3D models of reverse shoulder implants were created in order to perform finite element analysis (FEA). Therefore FEA is carried out in this study to find out whether or not the stress distribution on implants and micromotion between bone and implant at glenoid part cause the implant failure. It is hypothesized that the ROM of shoulder joint is altered with reverse shoulder implant. The abnormality of ROM of the implanted reverse shoulder joint is examined for abduction movement. Then it is investigated, if contact stress is high enough to cause wear of the humeral cup in glenohumeral joint or not. In order to simplify the analysis only abduction movement of shoulder joint is considered and the duration of the analysis was kept low in 4 seconds. The analysis proves that the peak stress generated of the humeral cup, which is made of polyethylene, can be as high as 25 MPa that exceeds the polyethylene yield strength. Polyethylene wear can be the result of this high contact stress. In addition to the permanent deformation and destruction of the component, one of the reasons for loosening of reverse glenohumeral joint is small particles from the polyethylene wear. Bone ingrowth can provide the long-term attachment between baseplate, which is attached to scapula, and bone after shoulder replacement, when the stable interface is maintained between bone and baseplate; and displacement of baseplate does not exceed 150 μm, which is a threshold value to allow bony ingrowth. The result also shows the parallel motion to the glenoid between baseplate component and scapula bone with 104 μm as maximum value. The micromotion does not exceed the limit value but as the obtained result is close to the threshold value to allow bony ingrowth, the probability of failure may arise under more sophisticated modeling conditions. Therefore, this knowledge will enable researchers, engineers and clinicians to improve the design of the reverse shoulder prosthesis.

Keywords: Reversed Shoulder Arthroplasty, Complications, Finite Element, Glenohumeral Joint, Stress Analysis

ÖZ

“Rotator Cuff” yırtılması ciddi ağrılara sebep olan ve omuz hareketlerini engelleyen, hastalar arasında en çok görülen vakalardandır. Günümüzde ağrıyı dindirmek, omuz eklemlerinin dengesini ve fonksiyonlarını düzenlemek için eklemleri protezler ile değiştirmek en fazla uygulanan tedavi yöntemidir. Fakat, normal omuz protezlerinin kullanımı omuz eklemlerinin hareketlerini düzenlemekte yetersiz kaldığı zaman kol kemiği ve kürek kemiği arasındaki ekleme ters omuz protezleri de takılmaktadır. Protez şekli göz önüne alınırsa, ters omuz protezleri, normal omuz protezlerinin tam tersi olup, küre kısmı kürek kemiğine, oyuk kısmı ise kol kemiğinin üst tarafına yerleştitilmektedir. Bu ters konumlandırmanın en önemli sebebi omuzu saran delta şeklindeki Deltoid kasının kolu kaldırma hareketinde daha aktif rol oynayabilmesidir. Bunun yanında, ters omuz protezlerinde de normal omuz protezlerinde görülen protez parçalarının gevşemesi ve çıkması gibi komplikasyonlar rapor edilmiştir.

Bu çalışmanın amacı kol kemiği ve kürek kemiği arasındaki yapay eklemin fonksiyonlarındaki aksamanın nedenlerini incelemektir. Böylece, hem yapay eklem protezlerindeki stres dağılımı hemde omuz hareketleri sırasında protez parçalarında görülebilecek mikro düzeydeki hareketler ve bunların yapay eklemin bozulmasındaki etkileri sonlu elemanlar kullanılarak analiz edilmiştir. Bu çalışmadaki hipotez yapay ve ters omuz ekleminin normal omuz hareketlerini sağlayamayacağı ve yüksek kontak stres ile protez parçalarının mikro hareketlerinin yapay eklem bozukluğuna sebep olabileceğidir. Bu değişiklikler özellikle kolun yukarıya doğru olan hareketi (abduction) sırasında incelenmektedir. Bu hareket doğrultusunda, kol ve kürek kemiği arasındaki yapay eklemde oluşan stesin aşınmaya neden olup olmadığı da incelenmiştir. Yapılan analizin süresini kısaltmak için omuz hareketi yalnızca dört saniyede sınırlı kalmıştır. Elde edilen sonuçlar en yüksek stresin kol kemiğine takılan ve özel bir tür polietilen olarak modellenen protez parçasında olduğu görülmüştür. Hareket sırasında kontak stresin 25Mpa gibi aşınmaya neden olabilecek yüksek bir değere ulaştığı ve bu değerin de modellemede kullanılan polietilenin akma mukavemetinden de fazla olduğu saptanmıştır. Bu sonuç kontak stresin protezde aşınmaya neden olabileceğini göstermektedir. Ek olarak, kol kemiğine takılan ve “Baseplate” adı verilen protez parçasının kolun yukarı hareketi sırasında mikro hareketleri incelenmiş ve en fazla mikro hareketin 100μm ve baseplate e paralel yöne olduğu bulunmuştur. Genel olarak protezin bozulmasına neden olan mikro hareket 150μm olarak kabul edilmekte ve bu çalışmada çıkan değere göre protezin bozulmasına neden olacak bir mikro hareket görülmemektedir. Fakat sonlu elemanlar analizi ve modellemesi daha sofistike olarak yürütülürse, mikro hareketlerin daha yüksek çıkma ihtimali olacaktır. Sonuç olarak bu tez için yürütülen çalışma ve elde edilen sonuçlar, araştırmacılara, mühendislere ve ortopedi klinik tedavi uzmanlarına ters omuz protezi tasarım ve geliştirilmesinde yardımcı olabilir.

Anahtar Kelimeler: Ters Omuz Artroplastisi, Komplikasyonlar, Sonlu Elemanlar, Kol ve Kürek Kemiği Eklemi, Stres Analizi

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LIST OF ABBREVIATIONS

3D	Three Dimensional
CPU	Central Processing Unit
CT	Computer Tomography
DOF	Degree of Freedom
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modeling
MRI	Magnetic Resonance Imaging
Pa	Pascal
RA	Rheumatoid Arthritis
ROM	Range of Motion

Chapter 1

INTRODUCTION

1.1 Functional Anatomy of Shoulder

Shoulder joint has the highest range of motion (ROM) in the body [1]. A complicated relationship of bony articulations, muscle forces and ligament constraints cause the movement of the human shoulder. There are lots of muscles, ligaments, tendons, cartilage and bones in shoulder girdle but here, most important parts are divided in three categories as follows:

1.1.1 Bony Anatomy

Most important parts of the bony anatomy are humerus, clavicle and scapula.

1.1.1.1 Humerus

Humerus is one of the main bones of the arm and it is the longest and largest bone of upper extremity. It attaches posteriorly to the scapula and distally to radius and ulna. Its proximal area includes the half-spheroid articulating surface or head, lesser tuberosity and greater tuberosity. The supraspinatus, infraspinatus and teres minor tendons are inserted into 3 facet of greater tuberosity. The subscapularis is attached to the lesser tuberosity [2].

Figure 1.1: Humerus

1.1.1.2 Scapula

Scapula or shoulder blade is a triangular, thin and large bone that is positioned on the posterolateral aspect of the thorax. Most important parts of the scapula that are used in the rest of this thesis are acromion process, coracoid process and glenoid cavity (glenoid fossa). Acromion process is located on the posterior side of the scapula. For deltoid function, the acromion serves as a lever arm and it also articulates with the distal end of the clavicle, which is called acromioclavicular joint. Coracoid process is a hook-like shape that is located on the superior anterior side of the scapula. Glenoid cavity is a shallow articular surface that is positioned on lateral angle of the scapula. It forms the glenohumeral joint of shoulder along the humeral head [2][3].

Figure 1.2: Scapula

1.1.1.3 Clavicle

The clavicle or collarbone is the only bony part that connects the body to the shoulder girdle. Medially it articulates with the sternum as the sternoclavicular joint. It also articulates laterally with the acromion process as the acromioclavicular joint. Its location is above the first rib [1].

1.1.2 Bony and Muscular Articulation

Glenohumeral joint, acromioclavicular joint and sternoclavicular joint are most important joints in the shoulder girdle. Acromioclavicular and sternoclavicular joints function and location are mentioned in the clavicle and scapula part.

1.1.2.1 Glenohumeral Joint

The glenohumeral joint, as the name suggests, is the joint between humeral head of humerus and the glenoid cavity of the scapula. This joint is assumed as a ball and socket joint and it is quite unstable joint because the head of humerus is relatively large where cavity of the scapula is shallow. At this joint, there are several movements, namely, abduction and adduction, flexion and extension, internal rotation and external rotation and circumduction, which are combination of flexion extension, abduction and adduction. The glenohumeral joint is primarily stabilized by rotator cuff muscles. Another powerful muscle, which play a major role not only in stabilizing the shoulder joint but also in a lot of the movements related to this joint is deltoid muscles [3][4].

1.1.3 Muscles or Dynamic Stabilizers

Rotator cuff muscles and deltoid muscles play the main role to stabilize the shoulder joint. And also for the movement of the humerus, deltoid muscles are the most functional muscles.

1.1.3.1 Rotator Cuff Muscles

Group of muscles, namely infraspinatus, supraspinatus, subscapularis and teres minor form the rotator cuff muscles. All of these muscles work together to stabilize the humerus head in to the glenohumeral joint. Dynamic interplay between these muscles and static stabilizer cause the 3D movements or rotations of the humeral head [4].

1.1.3.2 Supraspinatus Muscle

The supraspinatus muscle connects the tuberosity of the humerus to upper side of the spine of scapula. Elevation and abduction of the shoulder joint is operated by supraspinatus [4].

1.1.3.3 Infraspinatus Muscle

It emerges in the infraspinatus fossa, below the spine of scapula, and place on the posterior aspect of the greater tuberosity of the humerus. External rotation of the shoulder joint is achieved by it [4].

1.1.3.4 Teres Minor

Inferior aspect of the greater tuberosity of the humerus and lateral scapula border is connected together by teres minor muscle. It also helps to rotate the shoulder joint externally [4].

1.1.3.5 Subscapularis

Subscapularis muscle connects the lesser tuberosity of the humerus and anterior surface of the scapula together. It helps the humeral head of the humerus to move freely in the glenohumeral joint during elevation of the arm [4].

1.1.3.6 Deltoid Muscles

Deltoid muscle, which is one of the most powerful and important muscles in shoulder girdle, is divided into 3 main parts and each part has a different origin. The first one is known as clavicular part or anterior part, which is originated from the lateral third of clavicle. This muscle produces movement of arm and shoulder in forward direction, Internal rotation and adduction. Second part is known as acromial part or middle part of the deltoid muscle and it is originated from the acromion of the scapula. The main movement is associated to this muscle is abduction. The last part of the deltoid muscle is known as spinal part or posterior part and it is originated from the inferior border of the spine of the scapula. Moving arm and shoulder backward and external rotation is associated to this part. All 3 parts comes together and attached to the shaft of the humerus that is called deltoid tuberosity [4][5].

1.2 Biomechanics of Shoulder

In order to examine the shoulder kinematics of normal subjects, lots of researches have been carried out. However, motion of the shoulder complex is still arguable. Some researches explain the relative movements of the humerus to the scapula and some to the thorax. Complicated movements, which a fixed center of rotation is not defined for them, in human shoulder complex, make the kinematics of shoulder. Because of this complexity, the glenohumeral joint with three serial rotational joints are simply considered for shoulder complex. However, generally inner and outer shoulder joint is considered for the shoulder complex model. Inner shoulder joint consists of two perpendicular rotations and one translation, namely depression/elevation and retraction/protraction as rotation movements and a translation movement of scapula, respectively. Three perpendicular rotations, which are flexion/extension, abduction/adduction and internal/external rotations, with the axes intersecting in the center of the glenohumeral joint are defined for outer shoulder joint. Sagittal plane, which is a vertical plane and makes the body to right and left sections, is considered for measuring the flexion and extension movements. Maximum ROM of flexion and extension for healthy normal shoulder is 150°-170° and 40°, respectively. Abduction and adduction movements are measured in frontal plane, which passes side to side and makes the body to front and back sections. Maximum ROM of abduction and adduction movement for a normal shoulder is 160°-180° and 30°-40°, respectively. And the last one is horizontal or transverse plane that is considered to measure internal and external rotations. Maximum ROM of external (lateral) rotation is 95° in abduction and 70° in adduction movement for a healthy normal shoulder. Maximum ROM of internal (medial) rotation is 40°-50° in abduction and 70° in adduction movements [5][6][7].

Generally, reverse shoulder replacements are suggested for patients with rotator cuff tear. Recently, few researches have been done about the kinematics of reverse anatomy implants. Different types of reverse implants and variable subjects are considered for each research, separately.

In one of the researches 12 patients (6 males and 6 females, average age 75.1) with DELTA® III reverse shoulder replacements have been studied [46]. Their activities were recorded by an optical motion analysis system. 10 ADL, which were described by Murray (2004), were considered for the patients. In order to compare the ROM with normal shoulder, control group of 10 healthy subjects (5males and 5 females, average age 39.4) performed the same activities in the same clinical environment. A consistent range of humeral movement for all the ADL was seen for the normal group. Most of the ADL were performed by the prosthetic group completely, with a much more variable ROM. The average maximum humeral elevation was also obtained but with longer and variable time within the group. In almost every activity, there was smaller range of the humeral internal rotation (31.5° to 49.9°). Decreasing in humeral rotation is directly connected with the lack of rotator cuff muscles. However, by compensating with extra elevation, horizontal flexion and elbow, the patients were able to complete most of the ADL [8].

Other experimental researches have been performed on the patients with different types in reverse shoulder model. The lowest amount of maximum ROM for abduction and flexion movements are seen in Bayley–Walker reverse shoulder prosthesis with 64° and 73°, respectively; and the highest amount of maximum ROM for abduction is 120° and for adduction is 123° in DELTA® III reverse shoulder prosthesis [9].

1.3 Organization of the Thesis

This thesis comprises 6 chapters, the appendix and references. Functional anatomy of normal shoulder, which includes important bony parts and muscles around them, movement definition, and biomechanical comparison between normal and prosthetic shoulder is explained in Chapter1. In Chapter 2 literature survey is conducted and the biomechanical modeling of the shoulder joint, history, failure, components and complication of shoulder replacement are presented. Design steps of reverse shoulder joint components and the FE methods that are used, are described in Chapter 3. The results are demonstrated in Chapter 4 and discussed in Chapter 5. Finally, conclusion and suggestion for future work are presented in Chapter 7.

Chapter 2

LITERATURE REVIEW

2.1 Biomechanical Modeling of Shoulder Joints

Aim of the biomechanical modeling of shoulder is obtaining essential information about shoulder such as stress and strain that is appeared on intact shoulder joint parts to compare with the prosthetic shoulder parts. Modeling based information can be guidance for designers or surgeons to predict or prevent some complications after or during arthroplasty surgery and to help for proposing appropriate type, size and position of the shoulder prosthesis. In this way, for understanding and forecasting biomechanical occurrences, FE models are being used in medical research. FE has ability to analyze complex models that are hard to be studied experimentally [12][13].

In one of the researches, FE method was used to develop a numerical model of the shoulder to observe the influence of humeral head's shape on stress distribution in the scapula. It was a comparison between a healthy shoulder and an osteoarthritic shoulder, which is primary degenerative disease cause changing in bone shape. 3D rotator cuff muscles and 3D CT-reconstructed bone geometry were considered for the performed work. For the muscles and cartilage, linear hyperelastic model were applied as well as a non-homogenous constitutive model for the bones. Displacement of the active muscle produces external and internal rotations of the shoulders during the specific rotation.

Finally, as a result, posterior subluxation was observed for osteoarthritic shoulder joint during external rotation as compared with the normal shoulder joint. There was no posterior subluxation found. Distribution of stress in normal shoulder was homogeneous and the significant Von Mises stress in the posterior part of the glenoid area was determined. So, it can be concluded from this research that changed geometry of the pathological shoulder can be another reason of posterior subluxation for osteoarthritic shoulder in clinical situation like rigidification of the subscapularis muscle as often postulated [14].

In another research Madymo®, which is Mathematical Dynamic Modeling software package developed by TNO®, were used to analyze 3D forces and torques at shoulder joint during movement. An about 40 years old man with healthy shoulder was a volunteer with no prior shoulder joint disease, injury or disability. Essential data such as body weight, height and length of the right upper limb segments were obtained. In order to analyze forces and torques, obtained shoulder joint angles by in-house software were used as input data for the computer model to simulate the subject's movements. Two conditions were considered for this experiment. First condition was, standing in natural/comfortable position and moving right shoulder in abduction and flexion up to 90 degree, separately, extension and combination of flexion and adduction movements. Second condition had same steps but with having a 2.5 Kg. weight held in the right hand. Finally, shoulder joint force and torque were successfully predictable during movement by the model and also relationship between angles and torques were illustrated in a graph [15].

Some mechanical solicitations into the humerus are obtained in a research by analyzing glenohumeral joint during external and internal rotation for a healthy humerus and uncemented prosthetic humerus as a comparison between them. In order to gain deformation, stress, strain and other parameters on humerus, they used FE method by using ANSYS software. And also they considered all muscle groups involved during shoulder movements. They assumed Subscapularis, Latissimus dorsi, Teres major, Pectoralis major, Deltoidus and Brahialis as muscles during internal rotation and Infraspinatus, Teres minor, Deltoidus and Supraspinatus were involved as muscles during external rotation. 22N force, which was another assumption in research, was applied in each insertion point on humerus and the directions was chosen according to its insertion angles on humerus. Equivalent mechanical stress, equivalent strain and the total deformation were analyzed for both shoulder during internal and external rotation as result of the research. Maximum deformation had different place on humerus in prosthetic and un-prosthetic shoulders during external rotation. Proximal epiphysis was recognized as maximum equivalent strain region in both shoulders but it was located near the prosthetic head in un-prosthetic shoulder meanwhile it was located on humeral head for healthy shoulder. There were similar results for equivalent stress distribution for both shoulders type. Maximum stresses were observed into the proximal epiphysis on the humeral head for the healthy shoulder and, near the head at the junction between bone and prosthesis for the prosthetic shoulder. In the internal rotation movement, maximum deformation did not happen in the same humeral region. It was located at the center of diaphysis and below the center of the diaphysis, closer to the distal humerus for the healthy and prosthetic one, respectively. Distal epiphysis on the humeral head and proximal humeral epiphysis was region for maximum stress appearance, respectively.

Meanwhile, maximum equivalent strain was observed in the distal epiphysis for both types. As the numerical result were obtained for both type shoulders, there were lower numerical values for the obtained parameters in prosthetic one as compared to healthy type due to the stiffness induced by the prosthesis [16].

2.2 Need for Shoulder Joint Replacement

There are many reasons to consider shoulder joint replacement for patients who suffer from shoulder pain or having shoulder disability. Rotator cuff tear, osteoarthritis and fractures are the most common reasons for shoulder joint replacement. Keeping stable the glenohumeral joint and attach the humerus to the scapula is the main function of rotator cuff that consists of four muscles. Rotator cuff tendons due to existence of the bursa, which is a kind of lubricating sac between tendons and bone, glide easily when arm is moved. The humeral head is not completely attached to the rotator cuff tendons when one or more of the tendons are torn. So there will be some problems like instability of humeral head, Subacromial Impingement, which is because of proximal movement of humeral head, and the bursa can be inflamed [17][18]. Arthritis can be another reason for shoulder joint replacement. Osteoarthritis, which is progressively degeneration of cartilage that is a protection on bone surface, is the most common arthritis among them and million of the people around the world are affected by it [19]. The main reason of osteoarthritic is generally unknown however some factors such as overusing of shoulder like some sport activities, inflammation in shoulder joint and failure surgical management after previous shoulder surgery have been identified [19][20]. Fractures also can be mentioned as usual reasons for shoulder joint replacement. Generally, The fractures in shoulder girdle are divided in three parts. Proximal humerus, clavicle and scapular fractures, which is less common than the other categories. About five percent of all fractures are related to proximal humerus fractures and it is most common between females aged more than sixty years and the patients who have osteoporosis. Osteoporosis is bone disease that increases the risk of bone fracture. Eighty five percent of proximal humerus fractures are nondisplaced and it does not need operative treatment. Immobilizing shoulder with a sling while shoulder is being healed can be considered as one of the main nonoperative treatments [21]. The proximal humerus is made up of four parts in the Neer classification that includes humeral head, greater tubercle, lesser tubercle and humeral shaft. Two-parts, Three-parts and Four-parts are types of proximal humerus fractures that are depending upon the amount of displacement and angulation by fragment. 1cm displacement of fracture fragments and 45° or greater angulation between them is defined as a separated part for fragments. Fracture that causes separating between head of humeral and the shaft of humeral is the most common two-part fracture and also greater tuberosity fracture is another kind of two-part fracture. Clavicle fracture is usually occurred because of direct impact. For instance in contact sports and it is more common among young adults aged less than thirty. The weakest part in clavicle that is in more fracture exposure is the middle third of it. Fractures in medial one-fifth of clavicle, fracture in middle three-fifth of clavicle, which is included eighty percent of clavicle fractures and fractures in lateral one-fifth of clavicle are three types for these fractures that can be a guide treatment to identify specific risk at future complication. Scapula fracture in the shoulder girdle is uncommon due to existence of muscular coverage around it, representing 0.3 % of all fractures. Direct trauma is usually the main cause for this fracture. Scapular body and acromion fractures are result of direct trauma [21].

2.2.1 Treatment Methods of Shoulder Joint Problems

Generally, treatments are nonsurgical and surgical. The treatment is selected depending on the problem and patient's condition. Deciding about choosing one of the nonsurgical therapies depends on patient's pain level and disease intensity. Some common available nonsurgical treatment methods for the common disease like osteoarthritis are physiotherapy, activity like swimming and using of nonsteroidal anti-inflammatory drugs. It should be considered that related exercises to range of motion and joint mobilization procedure could be effective to relieve pain and to improve motion and also glenohumeral joint injections like steroid and hyaluronan are suggested for patients who cannot cope exercises [22]. For some fractures like humeral neck and scapular body fractures, surgical treatment is not suggested. Immobilizing the shoulder with using sling and local ice during fractures healing is suggested, and then mobilizing gently and exercising can be helpful. Additionally, some hands-on therapy like massage, dry needling and electrotherapy can be applied to heal shoulder function and to relieve pain [23]. If nonsurgical methods are unsuccessful, surgical methods such as reduction, internal fixation, total joint replacement and hemiarthroplasty can be suggested by surgeons for patients who have severe condition. In some conditions that there are no sufficient rotator cuff muscles, total shoulder arthroplasty is not more appropriate for patients, so surgeons consider reverse shoulder arthroplasty for these patients [24][25]. Currently reverse shoulder arthroplasty is mainly used for elderly patients and it is not suggested for young patients because of its complications. However, improvement in the moment arm of the deltoid muscle due to medialization of the center of the rotation and subsequently, active elevation of the arm independent of the rotator cuff are its advantages [26].

2.2.2 Shoulder Joint Revision Surgery

As the number of shoulder joint replacement or arthroplasty is increasing, demanding of revision surgery is being increased as well. There are number of artificial shoulder joint problems like, component malposition, infection, fracture and joint instability after primary arthroplasty that force surgeons to consider revision surgery [27]. So, several factors like patient's factors and expectations, implant failure and the etiology of implant should be evaluated when revision surgery is considered [28]. Before the reverse shoulder arthroplasty is introduced and approved, the failures were managed with unconstrained implants, fusion or resection arthroplasty. In a research, loss of forward flexion and external rotation after revision shoulder arthroplasty by using unconstrained prosthesis were observed [29]. In another research, group of patients who underwent revision arthroplasty using hemiarthroplasty method with poor bone stock on the glenoid, were studied. As compared with the patients had sufficient bone stock on the glenoid and total shoulder arthroplasty were operated for them, there were poorer outcomes and also the complication rate was high [30].

In a study 28 patients (30 shoulders) who consists 16 women and 12 men were followed up for a minimum 2 years. Patients underwent revision surgery reverse shoulder arthroplasty between 2005 and 2008 by same surgeon in same institution due to failed prior shoulder arthroplasty. Research included 11 shoulders were revised from a failed humeral head arthroplasty, 10 shoulders from a prior septic prosthesis, 8 shoulders from a failed total shoulder arthroplasty and 1 shoulder were revised from prior reverse shoulder arthroplasty. Revision surgery was considered for 21 right shoulders and 9 left shoulders. The range of group's age was 43 to 81 years (mean age of 64 years). Classic osteoarthritis in 33%, fracture-related in 30%, cuff tear arthropathy in 13%, capsulorrhaphy arthropathy in 17% and avascular necrosis in 7% were diagnosed as index operations. Additionally, more than one shoulder arthroplasty had operated in 17 shoulders and 13 shoulders had only one arthroplasty before revision surgery. Strength to forward elevation and range of motion, which was accessed in active forward flexion, abduction, external rotation, functional external rotation and internal rotation, were evaluated preoperatively and postoperatively. As a result, they observed improvement in all categories except in active external rotation, which there was not a significant improvement. In 80% of shoulders (24 of 30) the rating was very satisfied or satisfied. In conclusion with these performed researches and obtained results, reverse shoulder arthroplasty for revision surgery is reasonable method when instability, combination of bone loss and cuff deficiency is existed as compared to unconstrained prosthesis [31].

2.3 State of the Art of Shoulder Joint Implants

The first prosthetic shoulder arthroplasty was introduced in 1893 by Jules Emile Pe´an who is a French surgeon. A platinum and rubber replacement was implanted for a 37-year-old baker by Pe´an and there were a good result in strength and range of motion for patient after the surgery. After two years, infections were diagnosed and the prosthesis had been removed. Shoulder arthroplasty was not used mostly as a treatment for shoulder problems until, 11 out of 12 patients with fracture problem had been treated by Neer in 1955 with proximal humerus arthroplasty medication [31].

Total shoulder arthroplasty was first proposed in 1977 by Marmor. In 5 of Marmor's patients with rotator cuff tears, a superior migration was observed which led him to the proposal of total shoulder replacement. There are three different designed total shoulder implants by Neer. He considered a big ball as compared to the other types for increasing the motion in his first type that is called Mark1, although there was rotator cuff reattachment problem due to oversized ball. In the second type, which is called Mark2, the size of ball was changed to the smaller one for solving rotator cuff issue. However, decreasing in motion was the subsequent problem. Neer tried to get the motion in the third type that is called Mark 3, with adding axial rotation to the stem. However, this type had glenoid-loosening problem. Finally, Neer stopped designing prosthesis in 1974 with this conclusion that just constraint alone is not enough to recoup for a non-functional rotator cuff problem. During Neer's working years and after that, some researchers designed other type of implants with fundamental base and some modifications but most of them had problems, which led to implant failure such as scapular fracture and glenoid loosening. So due to these problems, researcher considered another difficult shoulder arthroplasty with reverse ball-and-socket design. They believed in improvement for motion and strength without increasing dislocation and loosening risk. Researcher tried to improve reverse shoulder implants with essential modifications for glenosphere and fixation configuration between 1972 and 1978. In 1972 Reeves et al. used divergent threaded peg in glenoid part and the center of rotation was placed which recreated the normal anatomic center. Kessel in 1973 used one central screw in glenoid and lateralized center of rotation. In 1975, Fenlin considered enlarged ball-and-socket would increase deltoid lever arm to compensate for the absent rotator cuff. These designs and modifications were continuing until Paul Grammont came up with new system that he put most his efforts on four keys features. Inherently stability for the prosthesis, concave shape for supported part and convex shape for weightbearing, considering a place at glenoid neck for the center of the sphere and medialization and distalization of the center of rotation. Grammont had three models of reverse prosthesis [32]. First reverse shoulder implant model, designed in 1985, included only two parts, metallic or ceramic ball which was fixed with cement and polyethylene socket. There were unsatisfied results in mobility for some of the patients. Because of these unsatisfactory results he considered some modifications for his second model such as changing glenoid to an uncemented system due to several failures for cemented glenoid part, using a central peg and some screws of divergent direction for glenoid fixation. The second model that called Delta III has been available from 1991. Due to experienced surgeries in reverse shoulder implantation and increased number of operations, Grammont led to generate his third model in 1994 that included direct modifications in humeral part. In summery, the concept of reverse shoulder arthroplasty has been introduced from 1970s, although the primary designing was unsuccessful. Grammont prostheses are fundamental for modern designing and modifications of reverse shoulder implants [32][33].

2.3.1 Parts of Reverse Shoulder Implant

There are lots of companies that produce reverse shoulder implants with little difference in shape, size and material. Generally, reverse shoulder prostheses include four or five main components. One of the components is glenoid baseplate, which is like a disk with rough surface that is coated by hydroxyapatite. Initial fixations are done with a central peg and four or six holes, which depend on company, are prepared to use peripheral divergent screws. The aim of the divergent screw design is to counteract the shearing forces during initial abduction. Glenosphere as another component is like a sphere that is made of cobalt-chrome normally. Morse taper system is used to fix it in baseplate. With two firm strikes by using specific tools, the glenosphere will be placed in baseplate and also it does not need screw for fixation. Humeral cup is another main part of reverse shoulder implants that is made of polyethylene and its diameter depends on diameter of glenosphere. There are no screws for fixation and it is press fitted onto humeral neck part. Humeral neck can be mentioned as fourth main part. It is generally made of titanium alloy and also it is available with a hydroxyapatite-coated surface or polished. Definitive humeral cup/humeral neck assembly is fixed onto stem with two firm strikes of humeral impactor. Different sizes are used depend on size of humeral cup. Finally, the last part is humeral stem, which is a conical rod. It is generally, made of titanium alloy or cobalt-chrome with polished or hydroxyapatite-coated surface for cemented or uncemented fixation, respectively. Inserting the stem in humeral canal is applied by using humeral inserter tool, which stem is assembled onto it. For cemented fixation, all processes is same, just before the inserting stem, humeral canal is filled with doughy cement [34][35].

2.3.2 Quality Control and Mechanical Testing

For making sure about reliability and longevity of products, it is essential to control the component's quality and also it is more important for medical component like prostheses to ensure that there is no failure or malfunctioning when they are implanted in patient's body. However there are some common testing standards such as International, American, British and European standards. In addition to those standards, simulating movement and motion of natural joints are essential. Additionally, prostheses are supposed to work for lifelong and it is difficult to test prototype for such a long period of time for shoulder prostheses. ASTM F2028 is one of the operated tests, which the EndoLab® performs for dynamic evaluation of glenoid loosening. There are two statics that are tested in subluxation mode and three dynamics, which are tested up to 100,000 cycles in loosening mode. Pivoting or rocking of glenoid component due to cyclic displacement of humeral head to opposing of glenoid rim is measured in this experiment [36]. Shoulder glenoid shear (ASTM F1829) is another EndoLab® shoulder prostheses testing to determine the static shear disassembly force of modular glenoid components. To compare with the other prostheses and as a design validation it is also used [37]. There are also another exclusive testing for shoulder prostheses such as wear test, range of motion, porous coating, fatigue test and modular connections but they are restricted to company, so reaching to the information is difficult.

2.3.3 Complications After Shoulder Joint Arthroplasty

Impingement of the medial border of humeral cup against the scapular neck during adduction and existence of polyethylene wear debris, which cause osteolytic reaction, are two mechanism that are explained as scapular notching, which is one of the common complications. First, Sirveaux described it in 1997 and later by De Wilde et al.'s research results demonstrated scapular notching in 48% of shoulders at one year after surgery, 60% at two years and the percentage was increasing over the time. However, the researchers are not sure about the evolution of scapular notching where clinical and radiographic result are arguable. Some investigations have shown the importance of inferior placement of glenoid part to avoid the impingement and scapular notching. It has been seen that changing the position of glenosphere to below the inferior glenoid rim decrease the severity of scapular notching. However, high grade notching was still noticeable in 15% to 20% of shoulders through applying this change [38][39][40][41]. Dislocation and instability are two of the shoulder complications seen after surgery that should be recognized by shoulder surgeons to determine a treatment to restore the stability**.** There are some main reasons for instability of reverse shoulder arthroplasty. Insufficient tension in deltoid muscle that cause Global decoaptation, which is an abnormal gap between ball and socket, can be one of the reasons for instability. This kind of instability can be treated with increasing the offset to restore deltoid muscle tension. By changing the glenosphere and cup to bigger size and adding humeral neck extension under cup, offset can be increased. Formation of hematoma in dead space under acromion after a reverse arthroplasty can be another reason for instability. In some cases, because of inserting liquid of hematoma between cup and glenosphere prosthesis, instability is observed. So, filling the dead space under acromion to avoid the collection of hematoma with considering a drain after implanting reverse shoulder prosthesis and placing the patients in abduction at 60° for three weeks are suggested by surgeons [42][43]. Finally, destruction of the anterior deltoid muscle or frequent atrophy during revision surgery that cause instability is another more common reason. So, in this case more prudent with postoperative rehabilitation should be considered. In an experimental research four hundred patients who treated with reverse shoulder arthroplasty followed during a four years period to evaluate the patients that sustained a scapular fracture [44]. Scapular fractures that can be mentioned as a complications after surgery are categorized into three different types as a result. Anterior acromion fractures that are due to lengthening of the deltoid muscle are classified as Type I. Superior humeral migration that cause immoderate erosion and previous acromioplasty have a weakening effect on acromion. Some standard postoperative rehabilitation is suggested as a treatment for these patients. During treatment after surgery, as the patient regains motion, a stress fracture maybe happens on posterior acromion joint, which is described as scapular fracture Type II, and it is due to stationary arthritic acromioclavicular joint. Internal fixation is used as a treatment and resection of the arthritic acromioclavicular joint, in most cases are suggested. Fracture Type III refers to scapular spine. Distribution of stress fracture from the tip of superior screw, which is placed in baseplate, as it pierced the posterior cortex of the scapula cause minor traumatic event that appearance of Type III fractures are result of it. So, because these fracture are result of superior placed screw's tip, it is recommended to not use superior screw if it is possible. Internal fixation is required as a treatment for this type of fractures [45]. Infection is also one of the most common complications after surgery not only after shoulder arthroplasty but also for most of the surgeries. Infection rate of 4% after reverse shoulder surgery in a series, which was one of the largest in the literature to 2007, with 199 patients from two surgeons have been reported [46][47][48]. Some factors such as revision surgery, hematoma formation, a larger Subacromial dead space and prolonged operative time are attributed to increased rate of infection. Another research on a database included 284 patients who 212 patients had undergone primary reverse shoulder arthroplasty and 72 of them had undergone revision RSA was performed. The average age of the patient was 66 years and there were 176 females and 108 males. All patients followed-up for minimum 12 months postoperatively and no patients recalled specifically for this research, so medical records and radiographs were used as a source for obtaining data. Finally, the infection rate in primary group (3 of 212) was lower than in the revision group (5 of 72). Additionally, infection rate for males were over twice as compared with females (4% vs. 2%) and age does not affect to infection rate [49]. And finally most common glenoid component complication in reverse total shoulder arthroplasty is the glenoid loosening but as compared to conventional total shoulder arthroplasty is less frequent. After 2 years follow-up, 4.1% has been reported as its prevalence [50]. And also in another report Cuff et al. mentioned 11% mechanical failure rate of the baseplate as using center of rotation lateralization at 21.4 months as an average [51]. Inappropriate positioning or insufficient fixation secondary to bone deficiency, age younger than 70 years, female gender and superolateral approach can be mentioned as risk factors for glenoid loosening. For decreasing the risk of glenoid loosening some parameter are considered such as using best available scapular bone for placing the screws, a larger central screw, multiple peripheral screws with larger diameter, locking screws and placement of the base plate inferiorly on the glenoid. Additionally, by removing the loose implant can relieve the pain but it does not improve shoulder function and also sufficient bone stock is required for direct glenoid component re-implantation [52].

2.3.4 Mechanism of Shoulder Implant Failure

For reverse shoulder failure discussion, it is better to divide failures to glenoid-side and humeral-side. Two common failures are described on glenoid-side as baseplate failure and glenosphere separation. Center of rotation of glenosphere, which is implanted to baseplate, and using fixation type of baseplate to scapula, are related to stresses on baseplate part. Herman et al. evaluated offset and fixation of glenosphere with respect to the forces and micromotion at interface between bone and baseplate. The researcher observed 65% increasing in moment at baseplate-bone interface by using glenosphere with a lateral center of rotation 27 mm from the glenoid as compared with traditional Grammont design [53]. Additionally, they noticed of the screw fixation effect on micromotion at interface. The authors proved that for limiting micromotion less than 150 microns at baseplate-bone interface, 3.5-mm screws are appropriate in Grammont-type design. However, when there was more lateral offset, the screws were unsuccessful at limiting the micromotion. With using 5-mm peripheral locking screws, the authors were able to show decreasing in micromotion. So maybe it describes almost 12% failures in some early series with lateral-offset glenosphere, which had 3.5-mm nonlocked peripheral screws fixation. Glenosphere dissociation, which happens less than baseplate failure, is other type of failure in glenoid-side. This kind of failure depends on the way that glenosphere is secured to the baseplate. In the early Grammont design, glenosphere and baseplate were fixed to each other by using the screws and in some cases simply dissociation were happened [54]. In more modern design, Morse taper system is substituted for screw fixation like the other orthopedic implants. However, there are still failures in some series, which Morse taper system is used, because of some reasons such as improper taper design or manufacturing, insufficient taper impaction and distraction forces in shoulder joint. Common failures on the humeral side are related to dislocation, failure in polyethylene cup and humeral stem loosening. Dislocation is one of the most common failures in humeral part side that revision surgery is necessary if it is unable to be treated by nonsurgical methods. Using inappropriate version of components can be one of the factors for instability. Some researchers suggest using different degree to placement component but the important thing to sure about stability is using match component version. Polyethylene cup failure after primary reverse shoulder arthroplasty is another failure in humeral side that will be treated by revision surgery. One of the reasons for this failure can be an impingement between humeral cup and scapula. Another failure that occurs in humeral side is humeral component loosening. Patients who have had hemiarthroplasty that was converted to reverse shoulder arthroplasty have more this failure as compared to other patients and it is due to bone loss of proximal humeral that is not reconstituted. So, forces from the constraint articulation joint are transmitted to the stem with diaphysis due to lack of metaphyseal support for the implant [55].

Chapter 3

MATERIALS AND METHODS

3.1 Creating 3D Models Using SolidWorks

In this thesis, SolidWorks® software is used to create reverse shoulder implants. Simple shapes that are similar to the currently used implants are designed. Geometrical properties regarding to the literature are considered. In this study, shoulder joint is combination of scapula and humerus as bony parts and baseplate, screws, glenosphere, humeral cup and humeral stem as implant parts.

3.1.1 Scapula

Scapula part is provided by university. Bone parts inserted in Geomagic software and surfaces modified to obtain a smooth surface (Fig. 3.1).

Figure 3.1: Scapula

3.1.2 Humerus

This part is provided by university. Computed tomography (CT) image obtained from the humerus is loaded into the software and it is modified to the 3D model. Mimics and Geomagic software are commonly used for these processes (Fig. 3.2)

Figure 3.2: Humerus

3.1.3 Baseplate

For creating a baseplate, 3 parts are needed. A cylinder with 30 mm diameter and 3 mm depth is created. 2 holes with 5 mm diameter are made on its surface on opposite sides by using hole wizard features. Another cylinder with 18 mm diameter and 4 mm depth is created with a hole in its center with 7.5 mm and 7 mm diameter and depth, respectively. Finally, for making screw a 30 mm length cylinder is used and with draft feature in edit surface it is changed to a cone shape. After that, screw is made by using helix feature in insert options and screw properties are defined for it. Fillet feature is also considered between two cylinders. Finally three parts are assembled as baseplate (Fig. 3.3).

Figure 3.3: Baseplate

3.1.4 Glenosphere

To create glenosphere, in 2D sketch a 36 mm diameter semicircle is created and with revolved boss/bass feature it is changed to a hemisphere. By using shell option, a 1.5 mm thickness is defined for hemisphere. In another sketch a cylinder with 9.5 mm length and 7.5 mm diameter is created. Finally, these two parts are assembled as glenosphere (Fig. 3.4).

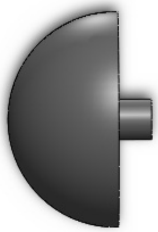

Figure 3.4: Glenosphere

3.1.5 Humeral Cup

To create humeral cup, 2 cylinders and one hemisphere as their designing process are explained in previous part are needed. First cylinder has 42 mm diameter and as it can see in the Fig. 3.5, 8 mm and 3 mm are considered as its depth in top and bottom, respectively. A 36 mm diameter shell is created into cylinder by using shell features. Second cylinder has 34 mm diameter and 2 mm depth. The last part for this assembly is a 35 mm diameter hemisphere. Finally, 3 parts are assembled as humeral cup (Fig. 3.5)

Figure 3.5: Humeral Cup

3.1.6 Humeral Stem

A 42 mm diameter hemisphere is created and it is changed to spherical shell with 35 mm inner diameter by using shell feature. In another 2D sketch, 2 parallel lines in 6 mm distance of each other with 30 mm and 35 mm length are created and they are connected together by 2 arcs. It is changed to the 3D part by extruded boss/base feature. Then these parts are assembled to one part as humeral stem (Fig. 3.6)

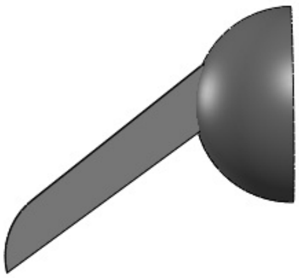

Figure 3.6: Humeral Stem

3.1.7 Screw

A hemisphere with 6 mm diameter is created. With line feature and extruded cut feature one side of hemisphere is cut. In cut side plane of hemisphere, a 3 mm diameter circle is created and with the extruded boss/bass feature it is changed to the cylinder. 26 mm length is considered for cylinder. The end of the cylinder with fillet/chamfer feature changed to the cone shape. Finally, by using helix and spiral feature in curves option, threads of screw are created (Fig. 3.7).

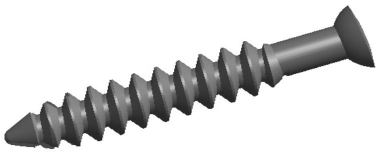

Figure 3.7: Screw

3.1.8 Final Assembly

For the assembly, all the parts are either scaled down or up in order to fit in the assembly. Figure 3.8 shows the final assembly created for the analysis.

Figure 3.8: Final Assembly of the Reverse Shoulder Model

3.2 Developing a FE Model of Reverse Shoulder Joint

Generally, it is important for both engineers and clinicians to understand each other for communicating. In order to get a successful communication they have to know the other one's subject-specific language and also to be familiar with fundamental terms. For instance, engineers need to know about clinician's input. Using ANSYS, FE analysis method is applied in this project. In order to decrease the computational time, some details that have minor effects on the final results were neglected or simplified. However, some minor details such as fillets or holes may be the area of maximum stress that is extremely important in the analysis and designing. Eventually, engineering judgment will decide how to balance loss of accuracy and computational cost in order to gain final result.

3.2.1 Meshing

For determining that a mesh is good or not, two aspects are considered. First one is about representation level of domain. Difference between final mesh and the areas or volumes of the actual domain is determined for this variable. Quality is the second aspect that regarding to relationship between the angles, length of edge, distance between specific element's point and etc., best element can be defined. Due to role of element quality on computational error in the simulation, it is emphasized in analysis. So, some quality criteria such as aspect ratio and the warping factor can be described to have a better idea about element quality. Ratio between the maximal and the minimal distance for each element is known as aspect ratio (AR). Then, the distances between element's faces must be determined to get the aspect ratio. Ideal element has a unit value as its aspect ratio (AR=1), and the element will be malformed if the AR reaches high values. For measuring the second parameter, which is warping factor (WF), the distances of the face's nodes to an average plane needed to be computed. Perfect element has the WF=0 and when all the nodes are coplanar, it happens. By increasing in WF value, there will be worse quality of the face and element.

Some research have been done to compare differences between types of meshing and to show advantages and disadvantages of them. Triangles and rectangles for two-dimensional problems, tetrahedral and hexahedral for 3D problems are commonly used.

Tetrahedral meshes, which are most used for medical field, are considered for model in this project.

3.2.2 Material Properties

Reverse shoulder implant parts that are explained in the previous subsections are used to model the reverse shoulder in this project (subsections 3.1.2 to 3.1.6). This model includes scapula and humerus as bony parts and 5 implant parts. Mechanical material properties are defined for each part with respect to appropriate materials that are used by researchers. All components are assumed to be as linear elastic and isotropic materials. By having two of elasticity parameters the other parameters can be obtained.

If Bulk modulus (K) is required:

$$K = \frac{2G(1+\nu)}{3(1-2\nu)} \tag{3.1}$$

$$K = \frac{EG}{3(3G-E)} \tag{3.2}$$

$$K = \frac{E}{3(1-2\nu)} \tag{3.3}$$

If Young's modulus (E) is required:

$$E = \frac{9KG}{3K + G} \tag{3.4}$$

$$E = 3K(1 - 2\nu) \tag{3.5}$$

$$E = 2G(1 + \nu) \tag{3.6}$$

If Shear modulus (G) is required:

$$G = \frac{3K(1 - 2\nu)}{2(1 + \nu)} \tag{3.7}$$

$$G = \frac{3KE}{9K - E} \tag{3.8}$$

$$G = \frac{E}{2(1 + \nu)} \tag{3.9}$$

If Poisson's ratio (υ) is required:

$$\nu = \frac{3K - 2G}{2(3K + G)} \tag{3.10}$$

$$\nu = \frac{3K - E}{6K} \tag{3.11}$$

$$\nu = \frac{E}{2G} - 1 \tag{3.12}$$

Where:

K is the Bulk modulus (Pa)

E is the Young's modulus (Pa)

G is the shear modulus (Pa)

ν is the Poisson's ratio

3.2.2.1 Scapula

Bone properties from the literature are defined for this component. All bone properties can be seen in Table 2.

3.2.2.2 Baseplate

Titanium alloy with properties that is represent in Table 3.1 is defined for the baseplate.

3.2.2.3 Glenosphere

Generally, CoCrMo alloy is considered for glenosphere. Mechanical properties of CoCrMo are defined in Table 3.1.

3.2.2.4 Humeral Cup

Normally, polyethylene or UHMWPE is used for the humeral cup. Polyethylene specification is described in Table 3.1.

3.2.2.5 Humeral Stem

Titanium alloy is considered for the humeral stem. Stiffness behavior of this part is defined as rigid. So, there is no meshing and analysis on this part. Titanium alloy properties are given in Table 3.1.

3.2.2.6 Humerus

Same as scapula, bone properties from the literature are defined for this component (Table 3.1). As the aim of this project is stress and strain behavior analysis at glenoid part and glenohumeral joint, stiffness behavior of humerus part is considered as rigid and there is no meshing and analysis of this part.

3.2.2.7 Screws

There are two screws that are used for fixing the baseplate into the scapula bone. Titanium alloy is considered as the material of screws. Properties of the titanium alloy are given in Table 3.1.

Table 3.1: Material Properties

Property	Unit	Titanium alloy	CoCrMo alloy	Polyethylene	Bone
Density	Kg m^{-3}	4430	7900	950	2100
Elastic modulus	Pa	1.138E+11	2.3E+11	1.1E+09	1.42E+10
Poisson ratio	_	0.342	0.29	0.42	0.3
Bulk modulus	Pa	1.2004E+11	1.9167E+11	2.2917E+09	1.1833E+10
Shear modulus	Pa	4.2399E+10	8.8462E+10	3.8732E+08	5.4615E+09
Tensile yield strength	Pa	8.8E+08	9.8E+08	2.5E+07	1.14E+08
Compressive yield strength	Pa	9.7E+08	_	1.4E+07	1.20E+08

Table 3.2: Material of Each Part of the Reverse Shoulder Model

Component	Material
Scapula	Bone
Baseplate	Titanium alloy
Glenosphere	CoCrMo alloy
Humeral cup	UHMWPE
Humeral stem	Titanium alloy
Humerus	Bone
Screws	Titanium alloy

3.3 Kinematic Properties

In order to define static and dynamic conditions of the shoulder components, for each part of the shoulder a joint is defined. And also contact properties between the connection parts are defined.

3.3.1 Joints

A fixed joint is applied at the top of scapula. Each screw is fixed to the baseplate, separately. By defining a fixed joint between baseplate and scapula, it is fixed to the scapula and there is no rotation and translation. A fixed joint is defined between glenosphere shaft and baseplate. Spherical joint as 3 DOF joint is defined between concave part of humeral cup and convex part of glenosphere and also there is fixed joint in the other side of humeral cup to humeral stem. Humeral stem is fixed to the humeral cup in one side and in other side it is fixed to the humerus part as well. So, movement of humeral cup, humeral stem and humerus are related together. Center of rotation for their rotatory movement is defined at the center of glenosphere. Humerus is just fixed to the humeral stem at one side.

3.3.2 Contacts

Several kinds of contact can be used in ANSYS, namely frictional, frictionless, rough, bonded and no separation. According to different characteristics of contact, there is different type of behavior in contact surface.

Between screws and baseplate, scapula and baseplate, glenosphere and baseplate, humeral cup and humeral stem, and humerus and humeral stem bonded contact is assumed. Separation and slide between surfaces are not allowed in bonded contact. Between glenosphere and humeral cup, frictionless contact is defined.

3.4 Constructing the Finite Element Models of Reverse Shoulder Joint

In this thesis ANSYS Workbench is used to analyze the stress and strain behavior at glenoid part and glenohumeral joint of reverse shoulder model. It is hypothesized that the ROM of shoulder joint may be altered with reverse shoulder implant [44]. Exceeded micromotion between scapula and baseplate, and polyethylene wear may cause failure of the implants [44][42]. The abnormality of the ROM of the implanted reverse shoulder joint is examined for abduction movement and it is investigated here if contact stress is high enough to cause wear of the humeral cup component of the glenohumeral joint or not. First, by using SolidWorks software some parts have been designed (subsections 3.1.2 to 3.1.6). Definitive model is imported for ANSYS to start analyzing (Fig. 3.8). As it is explained in the previous sections, material properties (Sec. 3.2.2), joints (Sec. 3.3.1) and contacts (Sec. 3.3.2) are defined for each part separately. Additionally, material properties, which are not exist by default in ANSYS, are added manually to ANSYS material library. Tetrahedrons meshing with path independent algorithm are considered for all parts, which are supposed to be analyzed. Anterior and middle deltoid muscles are represented by two spring elements that attach the scapula part to the humerus part with assigned spring constant of 3.3 N/mm [42]. So, forces at the glenohumeral joint during abduction movement are simulated by these two springs. Tensile force is given at the center of mass of upper limb, which includes the arm and shoulder. It is located on humerus part with magnitude about 30.12 N, which is equivalent to the mass of upper limb [47]. ROM of Abduction movement is limited by impingement on the acromion and scapular border superiorly and inferiorly in reverse shoulder model, respectively (Sec. 1.2). So, In order to simulate the abduction movement without impingement problem, 0° and 60° are considered as minimum and maximum degree of abduction movement, respectively [56]. A rotational movement with mentioned ranges is also defined at shoulder joint. So, the Von Mises stresses distribution between bone and implants at the glenoid parts and between humeral cup and glenosphere parts in abduction movement during shoulder joint movement are determined to figure out the maximum stresses that may cause the failure.

Chapter 4

RESULTS

Total shoulder replacement is considered for variety of shoulder problems as a treatment [40].

Over the past six years, increasing the use of reverse shoulder arthroplasty has been reported in the U.S. to restore shoulder function that is because of severe rotator cuff deficiency. Reverse shoulder is commonly used for older patients or as a last option in younger patients due to some complications after shoulder arthroplasty [57].

Bone fixation and correct positioning of the glenoid component can affect the survival of reverse shoulder prosthesis. Cut-out or scapular notching can be result of malposition or poor glenoid component fixation. However, the ideal position of the screws and baseplate are suggested by some researchers but it is technically difficult to find right placement due to complex geometry of scapula [41]. Loosening of Glenohumeral joint is one of the other failures in implants [18]. Polyethylene wear, which can be result of high contact stresses, is one of the reasons for the high rate of glenohumeral joint failure [58].

In this chapter, the results of Von Mises stresses on humeral cup, baseplate, screws and scapula components and also the micromotion between the baseplate part and scapula bone are presented. As it completely explained in Chapter 3 (Sec. 3.4), the whole reverse shoulder model is analyzed during abduction movement in 4 seconds and the obtained results for each part, which is supposed to be analyzed is presented, separately. Obtained results are discussed and compared to the literature in Chapter 5.

4.1 Von Mises Equivalent Stress

Due to a system of loads in 3D that is applied in an elastic body, a complex 3D system of stresses is appeared. Magnitude and direction of stresses are different in each direction. Von Mises formula calculates combination of stresses at a given point as an equivalent stress, which provides information about the maximum stresses that may cause failure of the implants. However, maybe none of the principal stresses exceed the yield stress of the material but failure is possible because of combination of stresses.

In this section, Von Mises stress distribution is calculated for each part separately during abduction movement of the shoulder joint.

4.1.1 Baseplate

Maximum Von Mises stress distribution on baseplate during abduction movement of shoulder joint in 4 seconds is occurred at t= 2.8 Sec., which is shown in Fig. 4.1. Maximum stresses distribution on baseplate is given in Table 4.1 and illustrated in Fig. 4.2.

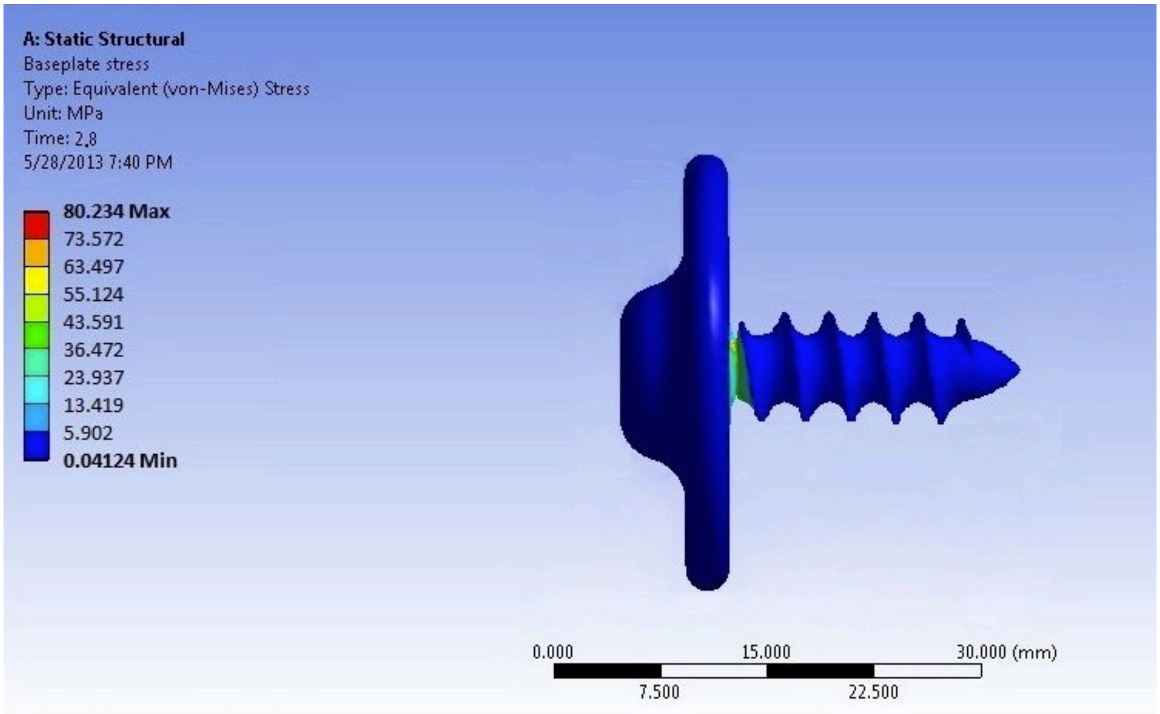

Figure 4.1: Stress Distribution on Baseplate During Shoulder Joint Abduction in 4 Seconds at $t = 2.8$ Sec.

Table 4.1: Maximum Stresses on Baseplate in 4 Seconds During Shoulder Joint Abduction

Time (s)	Maximum stress (MPa)
0	0
0.4	33.23
0.8	61.72
1.2	74.36
1.6	73.46
2.	75.86
2.4	78.92
2.8	80.234
3.2	79.38
3.6	77.23
4	74.12

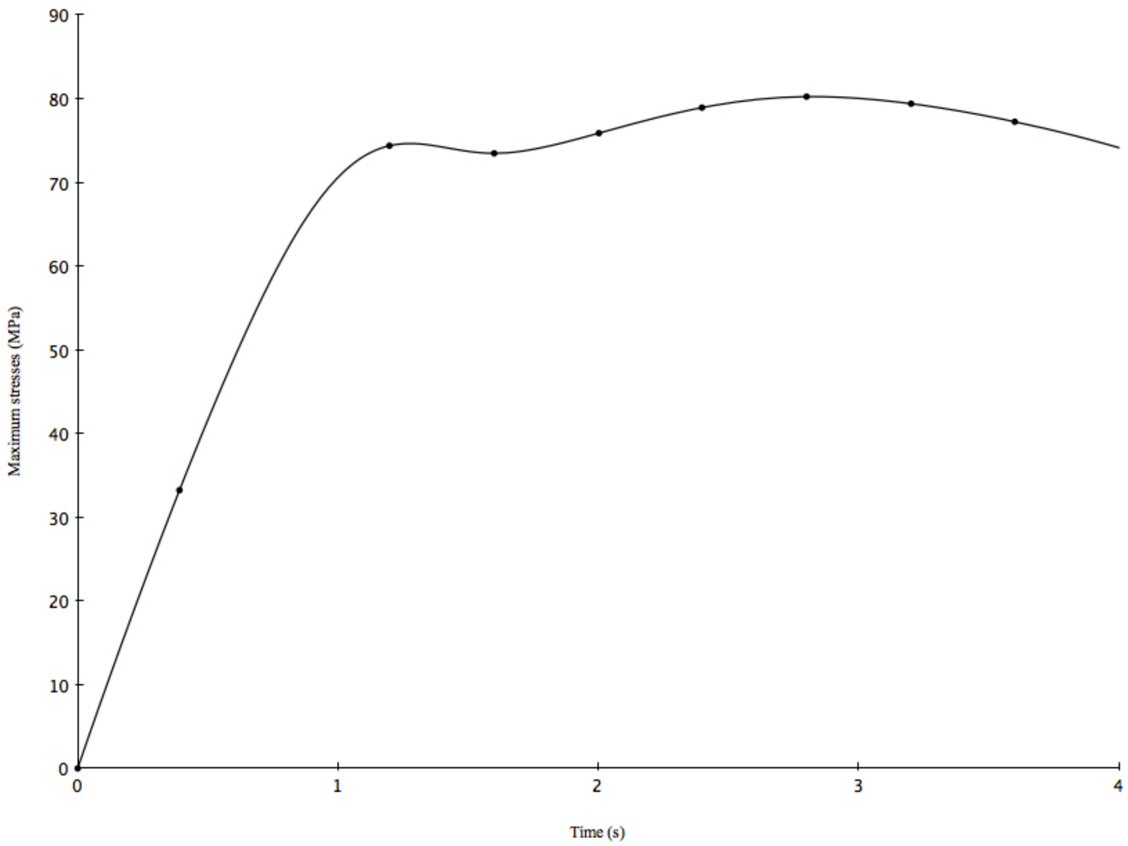

Figure 4.2: Maximum Stresses on Baseplate in 4 Seconds During Shoulder Joint Abduction

4.1.2 Inferior Screw

Maximum Von Mises stress distribution on inferior screw during abduction movement of shoulder joint in 4 seconds is occurred at t= 4 Sec., which is shown in Fig. 4.3. Maximum stresses distribution on inferior screw is presented in table 4.2 and it is demonstrated in Fig. 4.4.

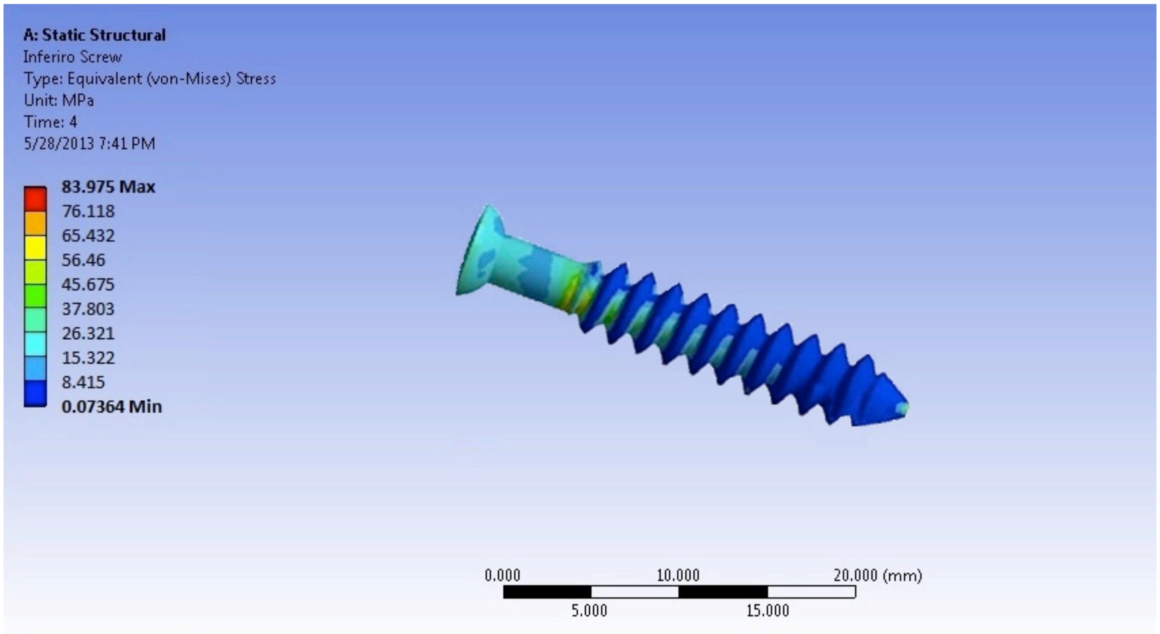

Figure 4.3: Stress Distribution on Inferior Screw During Shoulder Joint Abduction in 4 Seconds at t= 4 Sec.

Table 4.2: Maximum Stresses on Inferior Screw During Shoulder Joint Abduction in 4 Seconds

Time (s)	Maximum stress (MPa)
0	0
0.4	30.15
0.8	52.01
1.2	64.83
1.6	64.78
2	64.83
2.4	66.50
2.8	70.22
3.2	73.47
3.6	78.19
4	83.975

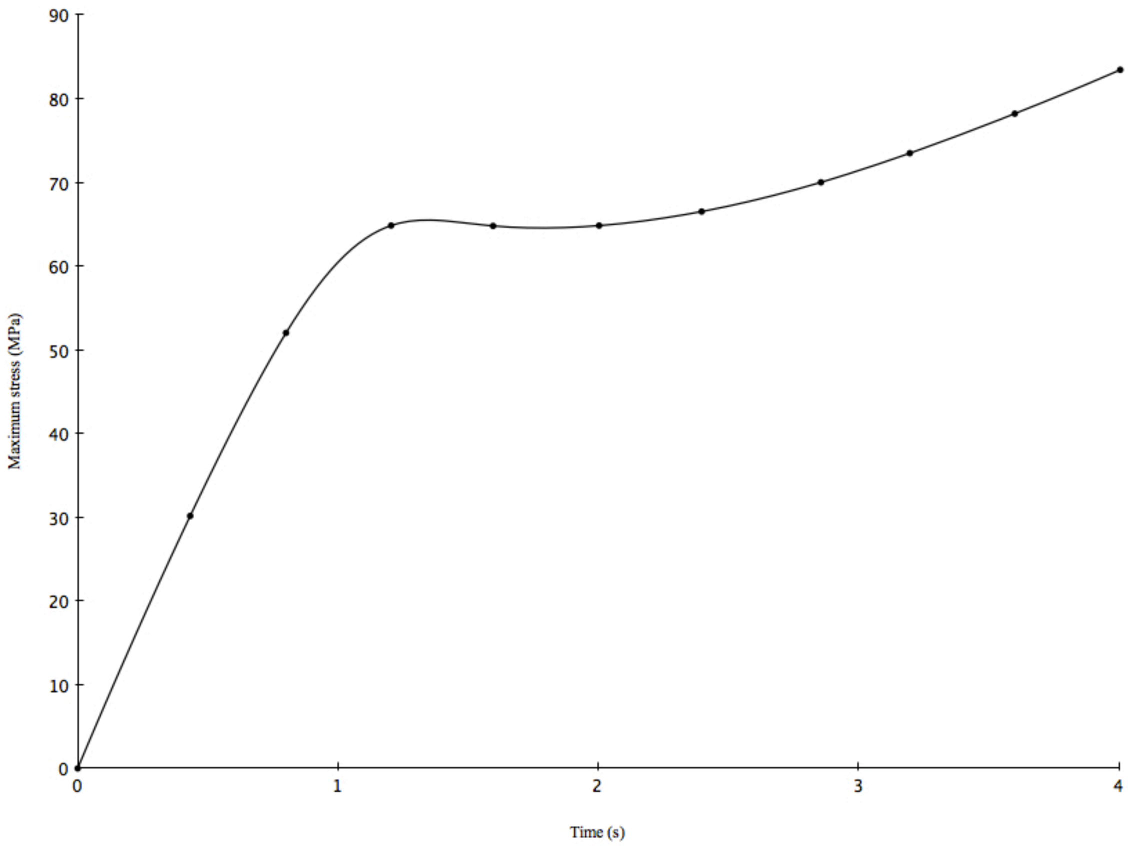

Figure 4.4: Stress Distribution on Inferior Screw During Shoulder Joint Abduction in 4 Seconds at t= 4 Sec.

4.1.3 Superior Screw

Von Mises stress distribution on superior screw during shoulder joint abduction movement in 4 seconds is occurred at t= 4 Sec., which is shown in Fig. 4.5. Maximum stresses distribution on superior screw is presented in table 4.3 and demonstrated in Fig. 4.6.

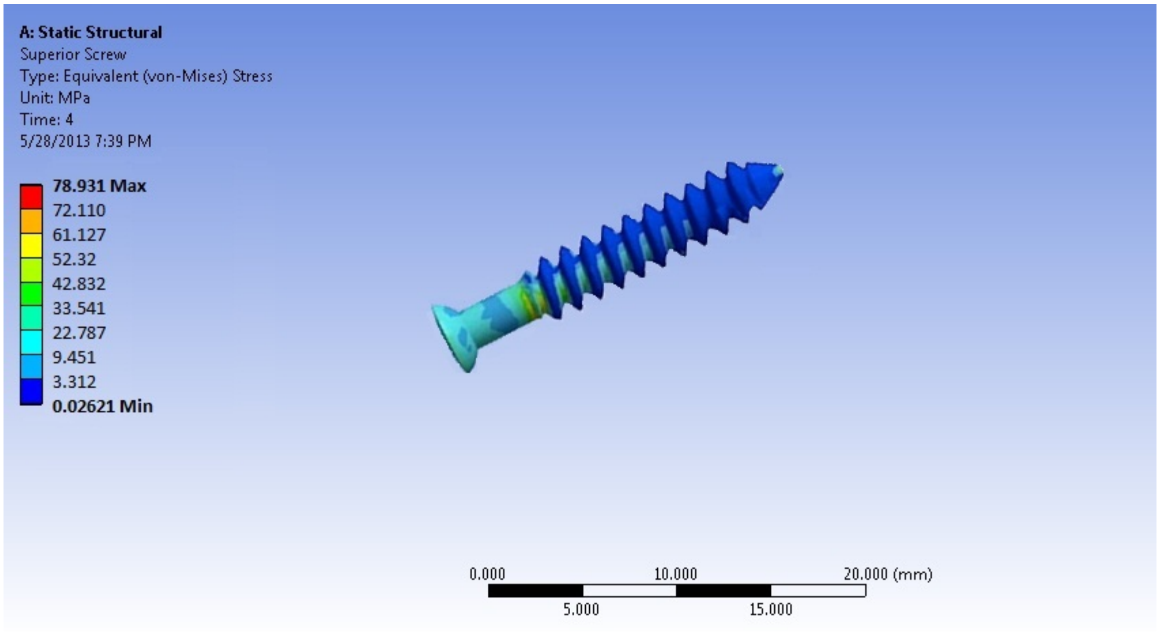

Figure 4.5: Stress Distribution on Superior Screw During Shoulder Joint Abduction Movement in 4 Seconds at t= 4 Sec.

Table 4.3: Maximum Stresses on Superior Screw During Shoulder Joint Abduction Movement in 4 Seconds

Time (s)	Maximum stress (MPa)
0	0
0.4	18.36
0.8	35.94
1.2	51.24
1.6	56.72
2	53.06
2.4	49.22
2.8	48.65
3.2	67.55
3.6	75.34
4	78.931

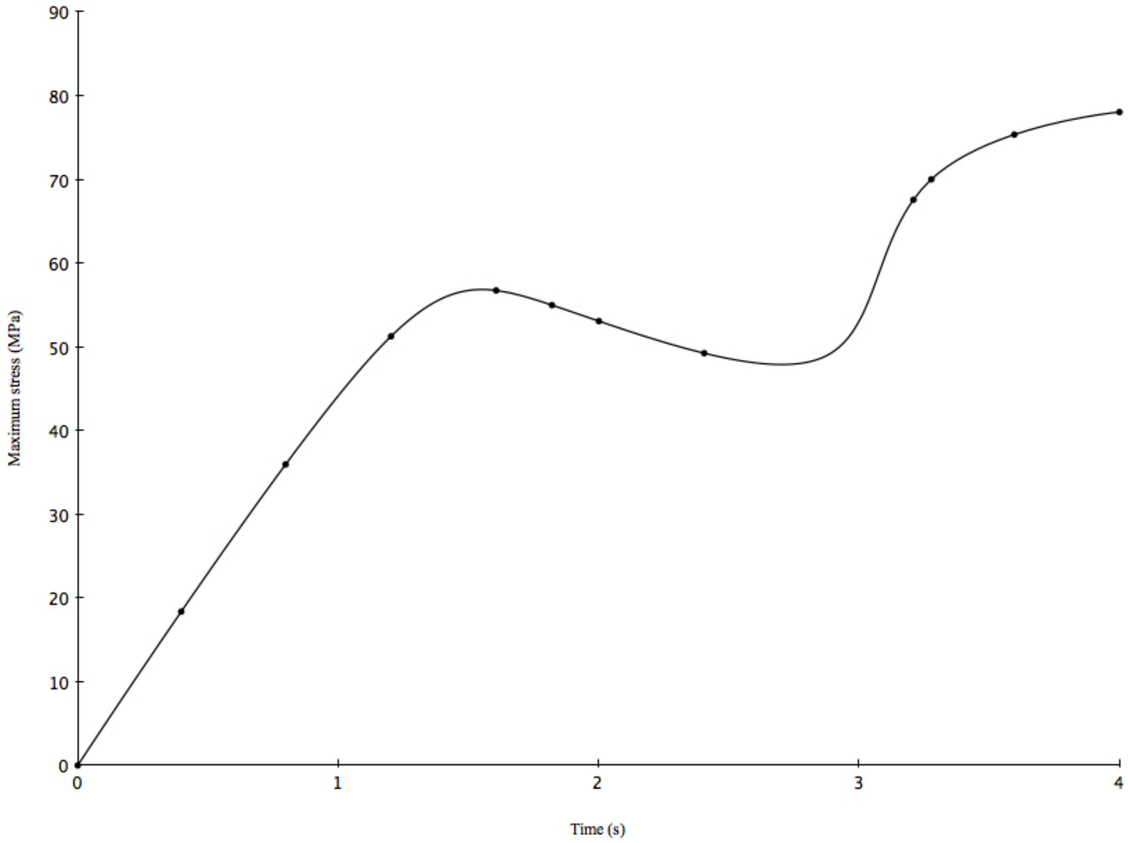

Figure 4.6: Maximum Stresses on Superior Screw During Shoulder Joint Abduction Movement in 4 Seconds

4.1.4 Glenosphere

Maximum Von Mises stress distribution on glenosphere during shoulder joint abduction movement in 4 seconds is occurred at $t = 2.4$ Sec., which is shown in Fig. 4.7. Maximum stresses distribution on glenosphere is presented in table 4.4 and illustrated in Fig. 4.8.

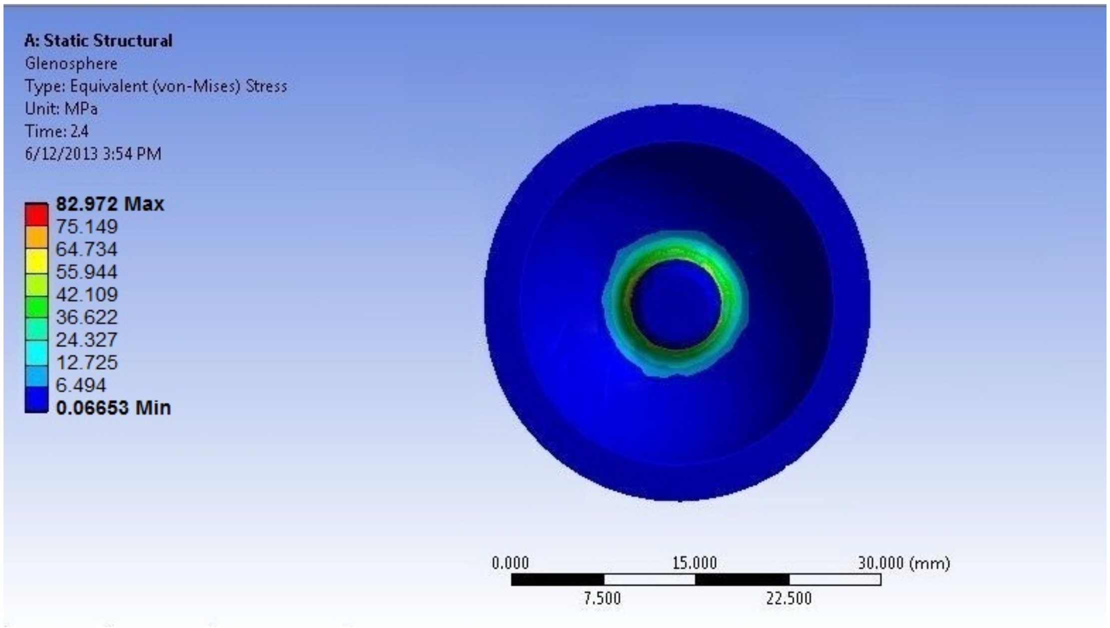

Figure 4.7: Maximum Stresses on Glenosphere During Shoulder Joint Abduction Movement in 4 Seconds at $t = 2.4$ Sec.

Table 4.4: Maximum Stresses on Glenosphere During Shoulder Joint Abduction Movement in 4 Seconds

Time (s)	Maximum stress (MPa)
0	0
0.4	36.35
0.8	48.09
1.2	58.11
1.6	68.26
2	77.44
2.4	82.972
2.8	81.48
3.2	81.14
3.6	77.45
4	72.38

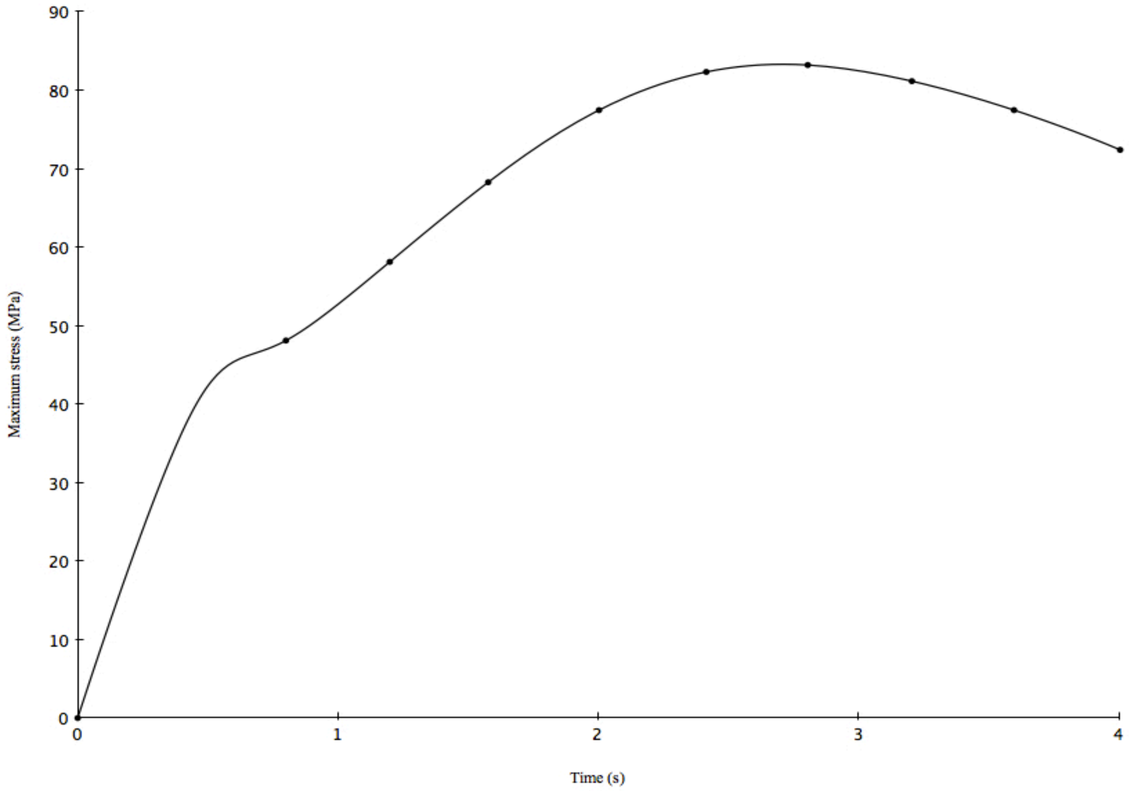

Figure 4.8: Maximum Stresses on Glenosphere During Shoulder Joint Abduction Movement in 4 Seconds

4.1.5 Humeral Cup

Maximum Von Mises stress distribution on humeral cup during shoulder joint abduction movement in 4 seconds is occurred at $t = 4$ Sec., which is shown in Fig. 4.9. Maximum stresses distribution on glenosphere is presented in table 4.5 and illustrated in Fig. 4.10.

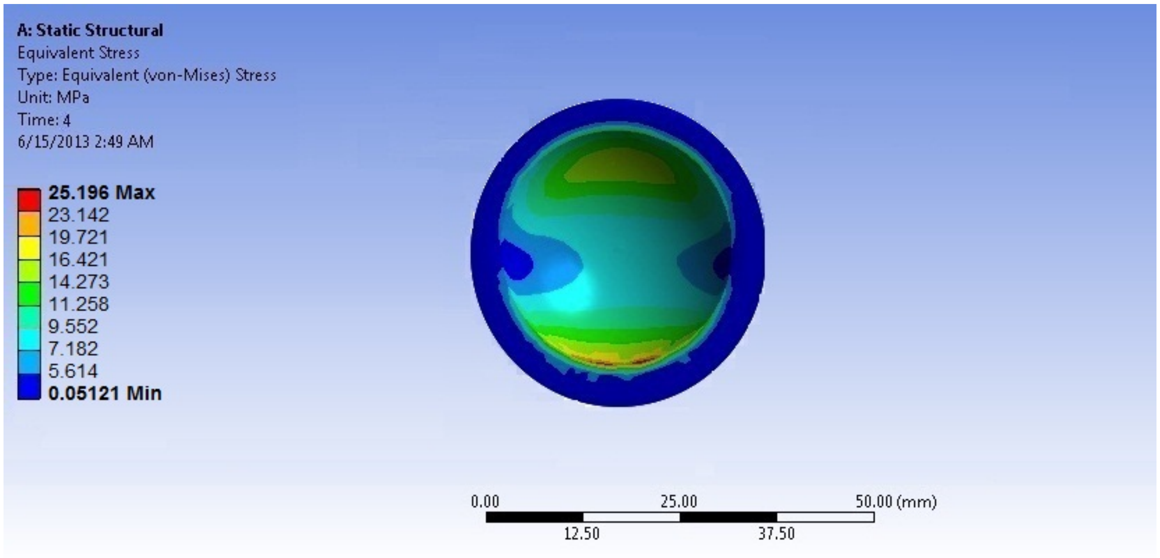

Figure 4.9: Stress Distribution on Humeral Cup During Shoulder Joint Abduction Movement in 4 Seconds at t = 4 Sec.

Table 4.5: Maximum Stresses on Humeral Cup During Shoulder Joint Abduction Movement in 4 Seconds

Time (s)	Maximum stress (MPa)
0	0
0.4	5.82
0.8	9.08
1.2	12.04
1.6	13.60
2	15.14
2.4	16.94
2.8	18.24
3.2	19.71
3.6	21.92
4	25.196

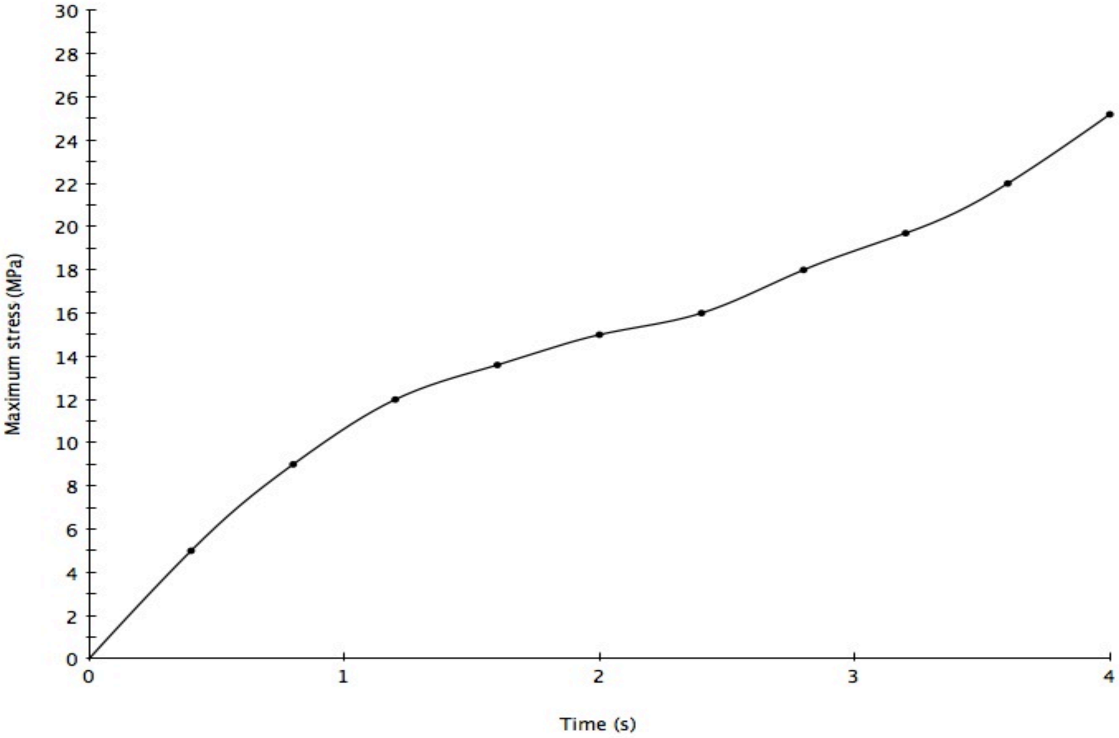

Figure 4.10: Maximum Stresses on Humeral Cup During Shoulder Joint Abduction Movement in 4 Seconds

4.1.6 Scapula

Maximum Von Mises stress distribution on scapula during shoulder joint abduction movement in 4 seconds is occurred at $t = 4$ Sec., which is shown in Fig. 4.11. Maximum stresses distribution on glenosphere is presented in table 4.6 and illustrated in Fig. 4.12.

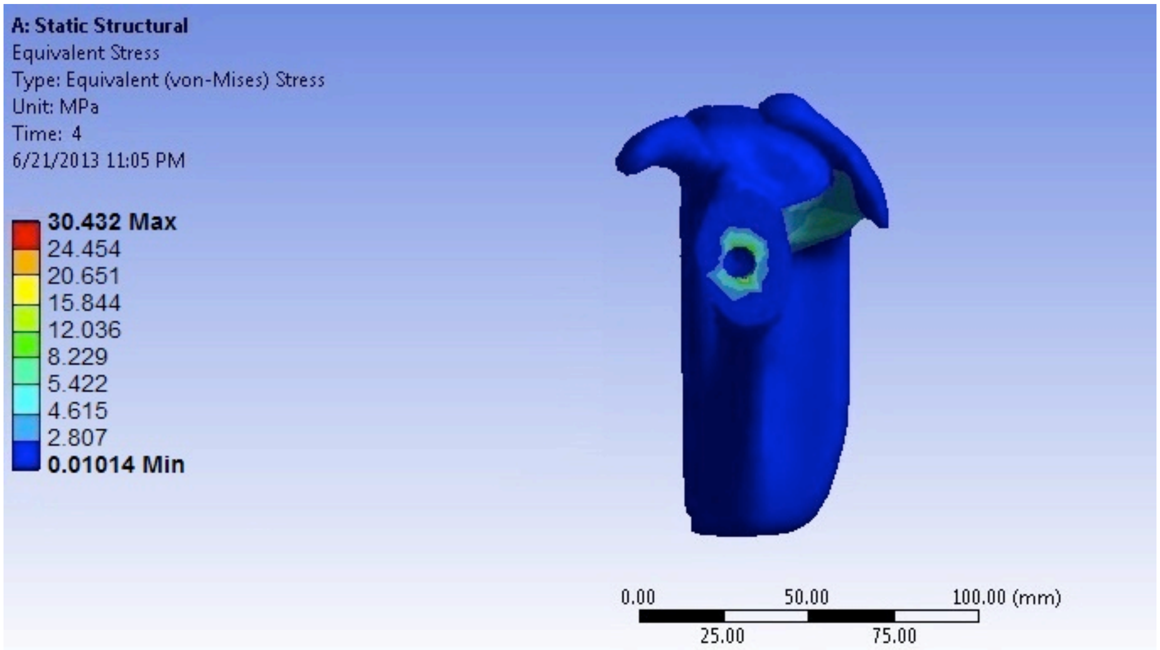

Figure 4.11: Stresses Distribution on Scapula During Shoulder Joint Abduction in 4 Seconds at t = 4 Sec.

Table 4.6: Maximum Stresses on Scapula During Shoulder Joint Abduction in 4 Seconds

Time (s)	Maximum stress (MPa)
0	0
0.4	3.52
0.8	4.37
1.2	7.31
1.6	9.63
2.	10.82
2.4	12.07
2.8	16.47
3.2	20.72
3.6	28.83
4	30.432

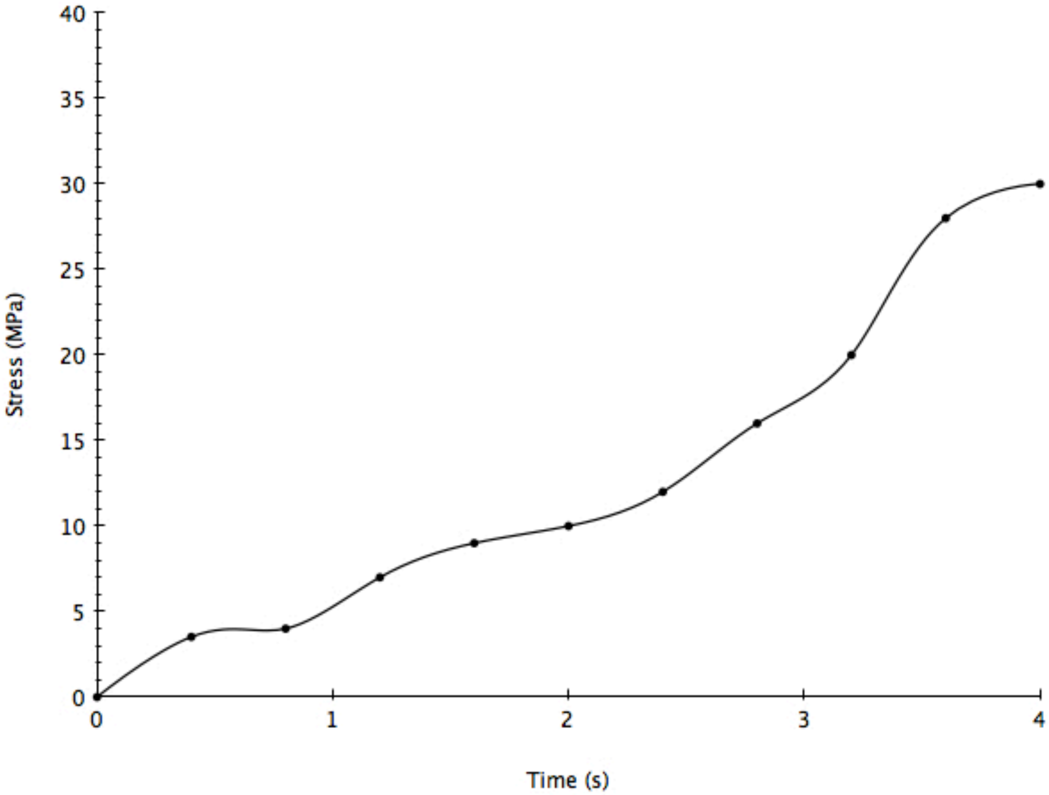

Figure 4.12: Maximum Stresses on Scapula During Shoulder Joint Abduction in 4 Seconds

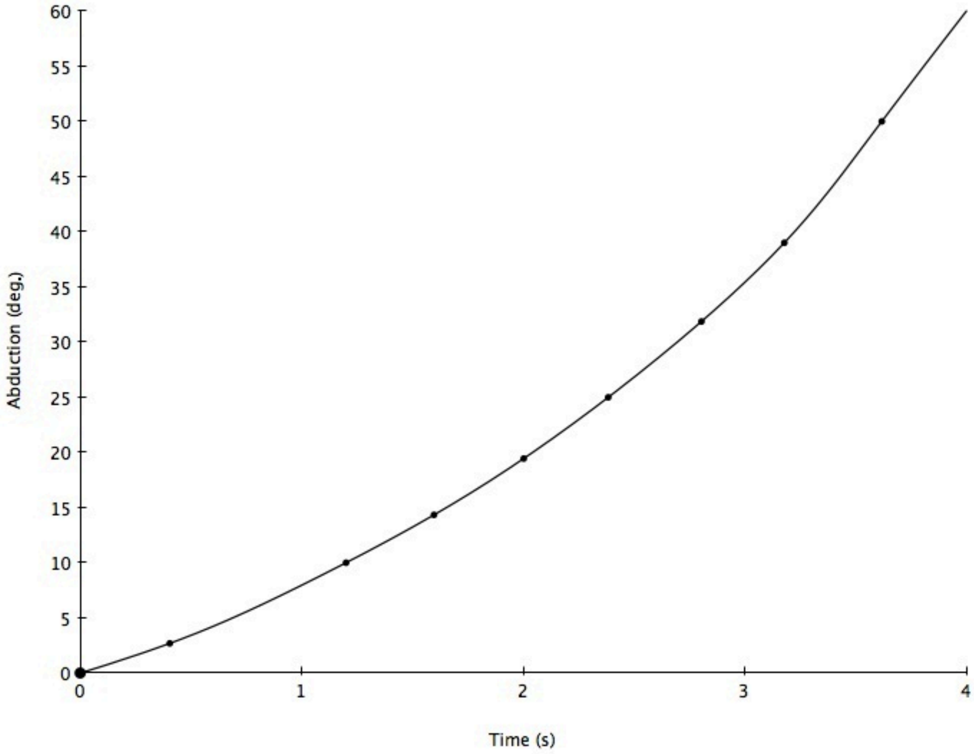

Figure 4.13: Abduction Movement of Shoulder Joint in 4 Seconds

Table 4.7: Abduction Movement of Shoulder Joint in 4 Seconds

Time (s)	Abduction (deg.)
0	0
0.4	2.68
0.8	6.12
1.2	9.96
1.6	14.33
2	19.43
2.4	24.93
2.8	31.86
3.2	38.34
3.6	49.23
4	60

4.2 Micromotion Analysis

Exceeded displacement between baseplate and scapula bone may cause failure. Long–term attachment is provided between glenoid bone and baseplate by bone ingrowth, if a stable interface is maintained. However, ingrowth becomes interrupted and there will be failure ultimately, if excessive motion is produced at the bone/baseplate interface by forces [59][60].

In this section it is decided to analyze the displacement of baseplate parallel to the glenoid between baseplate and scapula. This displacement is along z-axis, which is perpendicular to the horizontal plane. The same condition, which is shoulder joint abduction movement in 4 seconds with same static and dynamic conditions, are considered for this analysis as well (Sec. 3.4). Results are discussed and compared to the literature in Chapter 5.

Table 4.8: Baseplate Motion Parallel to Glenoid (Along z-Axis) During Shoulder Joint Abduction in 4 Seconds (Value Below 0 μm Show Displacement in the Inferior Direction)

Time (s)	Relative Displacement (μm)
0	0
0.4	29.32
0.8	48.50
1.2	80
1.6	98
2	104
2.4	60
2.8	32
3.2	30
3.6	0
4	-20

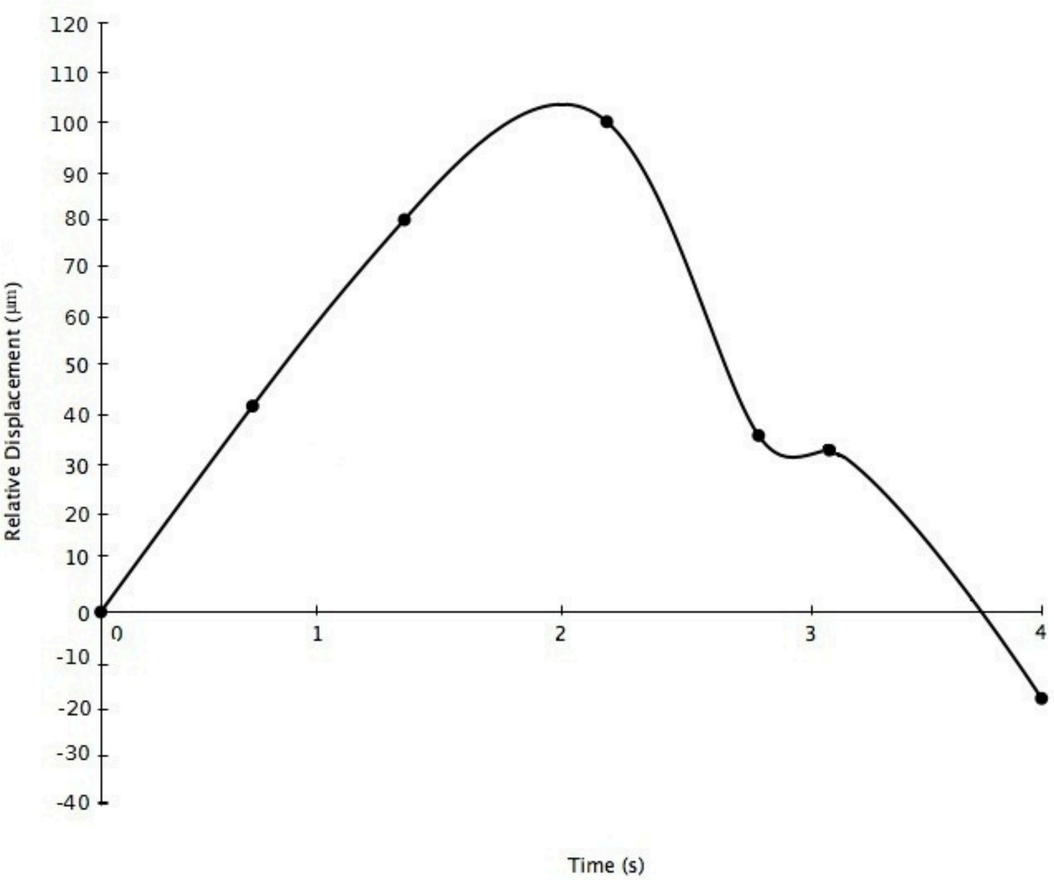

Figure 4.14: Baseplate Motion Parallel to Glenoid (Along z-axis) During Shoulder Joint Abduction in 4 Seconds (Value Below 0 μm Show Displacement in the Inferior Direction)

Chapter 5

DISCUSSION

Results that are obtained in Chapter 4 are discussed in this chapter. Two screws, baseplate, glenosphere, humeral cup and scapula were considered for analysis. Some assumptions were also considered to simplify the model in order to decrease the processing time and CPU usage of the analysis. These assumptions include:

- Only abduction movement of shoulder joint was considered and the duration of the analysis was kept low in 4 seconds.
- Because the analysis was performed just at the glenoid part, stiffness behavior of humerus and humeral stem was considered as rigid.
- As it explained in chapter 1, there are rotational and transitional movements for scapula bone, but in this analysis a fixed joint is considered for it.

5.1 Discussion of the Results

Glenohumeral joint loosening and hardware failures in components between baseplate and scapula interface are main impediment to success of reverse shoulder arthroplasty. So, in order to find out the probable failures, two analyses were considered for the model. The results include Von Mises stress distribution on components and micromotion between baseplate and scapula during shoulder joint abduction movement and the duration of the analysis is 4 seconds.

5.1.1 Von Mises Stress

However, stresses vary at different points in X, Y and Z directions that may not cause failure in parts but combination of them which is Von Mises stress may cause failure. So, Von Mises criterion is considered for this analysis.

According to the result Maximum Von Mises stress on humeral cup is 25.1 MPa and this exceeds polyethylene yield strength. This value of stress may cause polyethylene wear in humeral cup component. So, debris resulting of polyethylene's wear might be one of the reasons for the high rate of glenohumeral joint loosening. Results are close to the results of Bednarz et al. who had FE element analysis between humeral cup and glenosphere with different glenosphere types to find out contact stress on humeral cup during abduction movement. Their maximum Von Mises stress result on humeral cup is 25.6 MPa. The difference between the results is because of some different conditions like force magnitude and geometries of components.

Maximum Von Mises stresses among scapula bone, screws and baseplate is on inferior screw during shoulder joint abduction with value of 83.975 MPa. The maximum stress was occurred at the end of the analysis. (In t=4s and 60° of abduction).

With only 4 % difference, obtained result is close to the result of Yang et al. with 87 MPa for maximum values on inferior screw during abduction movement of shoulder joint. Yang's analysis during abduction movement of shoulder joint was between the range 0° to 45° which is the main reason of the difference between the results.

In another experimental research by Chebli et al. about the fixation of the glenoid component in reverse shoulder prosthesis, location of maximum Von Mises stress which is concentrated on the inferior screw was close to this study. So, with regards to the results and literature the inferior screw, which is on risk of the probable failure, is the most important part among the screws and baseplate components.

5.1.2 Micromotion Analysis

Providing a stable interface between the bone and the prosthetic component during initial healing as a biomechanical prerequisite is necessary to have a successful osseous integration for fixation. Exceeded displacement between baseplate and scapula bone may cause failure. So, in this section the obtained results from the Chapter 4 (Sec. 4.3) are discussed and compared to the other researches.

According to the results the maximum relative displacement parallel to glenoid (along z-axis) at the bone/baseplate interface is 104 μm in t=2s and 19.43° of abduction in superior direction during shoulder joint abduction. After t=2s and 30° of abduction it starts to decrease (Fig. 4.14).

Commonly accepted maximum motion that allows effective bony ingrowth is 150μm. So, obtained results in this thesis show micromotion parallel to the glenoid bone at bone/baseplate interface does not exceed the limit of 150 μm (Sec. 3.4), but under more realistic conditions such as applying bigger forces on humerus bone as an extra weight or different ROMs, the probability of failure may arise.

Obtained results are close to the results of Nazeem et al. who had researched in vitro and conducted a FE analysis of glenoid bone/baseplate interaction in reverse shoulder design during abduction movement. Maximum displacement parallel to the glenoid at the bone/baseplate interface was 96 μm for the FE analysis and 120 μm for the mechanical testing. The models were analyzed during abduction movement of shoulder joint.

Gutiérrez et al. also had researched on hardware failure in reverse shoulder prosthesis during abduction movement. Maximum displacement at the bone/baseplate interface in superior direction was 80 μm, and it was 15 μm in inferior direction. The inferior displacement in their research is because of considering higher range of motion for the abduction movement.

Obtained results of this study have 4 % difference with the results of Nazeem et al. and 20 % with the results of Gutiérrez et al. Simplifying of geometries, lower quality of meshing and using different force magnitudes are reasons for differences in the results.

Chapter 6

CONCLUSION AND FUTURE WORK

In this thesis, a 3D reverse shoulder joint was designed using SolidWorks. The model was analyzed in ANSYS to find the probable failures in shoulder joint. Von Mises stress and displacement parallel to the glenoid at bone/baseplate interface was calculated and compared with the previously published works.

The model was simplified and some assumptions were considered for this analysis due to lack in availability of high capacity CPU. By comparing the results to other literature results, we see that results are in the acceptable range and thus the FE reverse shoulder joint was developed correctly.

According to the results, the peak stress generated on humeral cup component under the assumed conditions can be as high as 25 MPa. Humeral cup component is made of polyethylene. The obtained maximum stress on humeral cup exceeds the polyethylene yield strength. So, polyethylene wear is possible in this condition. One of the reasons for the high rate of glenohumeral joint loosening found clinically, can be the debris resulting from the polyethylene wear.

And also regarding the results, Maximum Von Mises stresses among scapula bone, screws and baseplate is on inferior screw during shoulder joint abduction with value of 83.975 MPa. So, inferior screw has the most probability to fail compared to other parts.

Exceeded displacement between baseplate and scapula bone may cause failure. Bone ingrowth can provide the long-term attachment between baseplate and bone after shoulder replacement, when the stable interface is maintained between bone and baseplate; and displacement of baseplate does not exceed 150 μm, which is a threshold value to allow bony ingrowth. Relative displacement between baseplate and scapula is calculated during abduction movement. The result was 104 μm. So, there is stable fixation between scapula and baseplate in static and dynamic conditions of this thesis. As the obtained result is close to the threshold value to allow bony ingrowth, the probability of failure may arise under more realistic conditions.

In order to get accurate results, it is suggested to define a translation movement for scapula to make it more similar to the anatomic shoulder. Considering the ligaments around the shoulder joint and defining more realistic contact parameters between joints can be effective for the results. Better quality meshing is also suggested for the model to increase accuracy of the results.

As a future research, diameter and length of screws and relative angles of the screws to the baseplate central axis can be analyzed to find out its effect on maximum stresses and micromotion between baseplate and scapula; also components types, components thicknesses, positioning of the glenosphere and baseplate in scapula can be analyzed to evaluate their effects on contact stress in glenohumeral joint.

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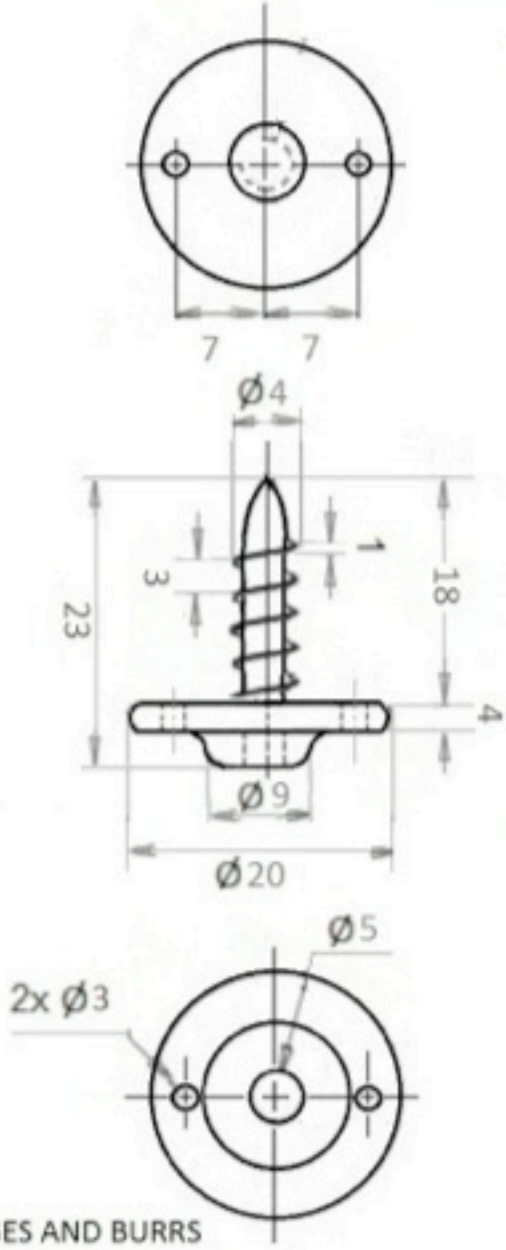
APPENDICES

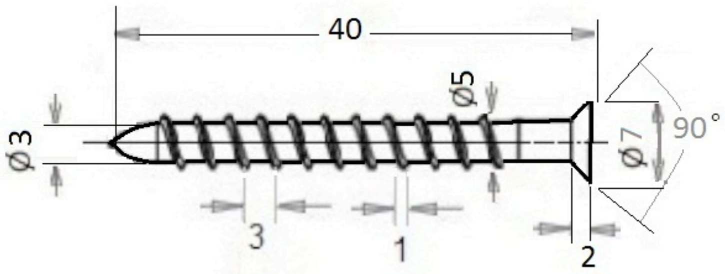
Appendix 1



REMOVE ALL SHARP EDGES AND BURRS
ALL FILLETS AND ROUNDS R3

	NAME	DATE	SIGN	EMU
DRW. BY	S.E	23.07.213		
CHK. BY	DR. H.H			
SCALE 1.1	BASEPLATE			DRW NO 1.1

Appendix 2

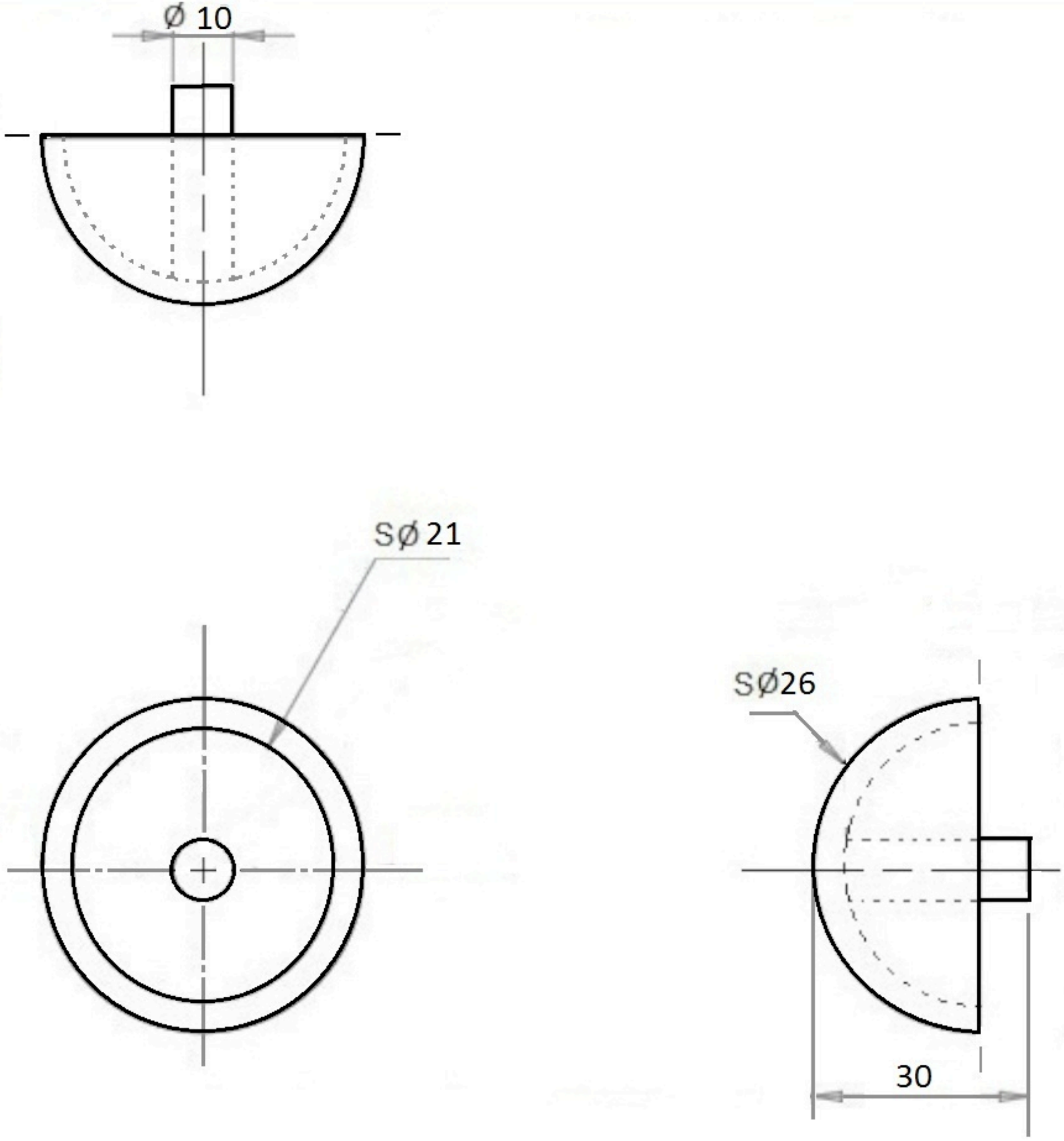


FLAT HEAD CROSS RECESSES

REMOVE ALL SHARP EDGES AND BURRS
ALL FILLETS AND ROUNDS R3

	NAME	DATE	SIGN	EMU
DRW. BY	S.E	23.07.213		
CHK. BY	DR. H.H			
SCALE 1.1	SCREW			DRW NO 1.2

Appendix 3



REMOVE ALL SHARP EDGES AND BURRS
ALL FILLETS AND ROUNDS R3

	NAME	DATE	SIGN	EMU
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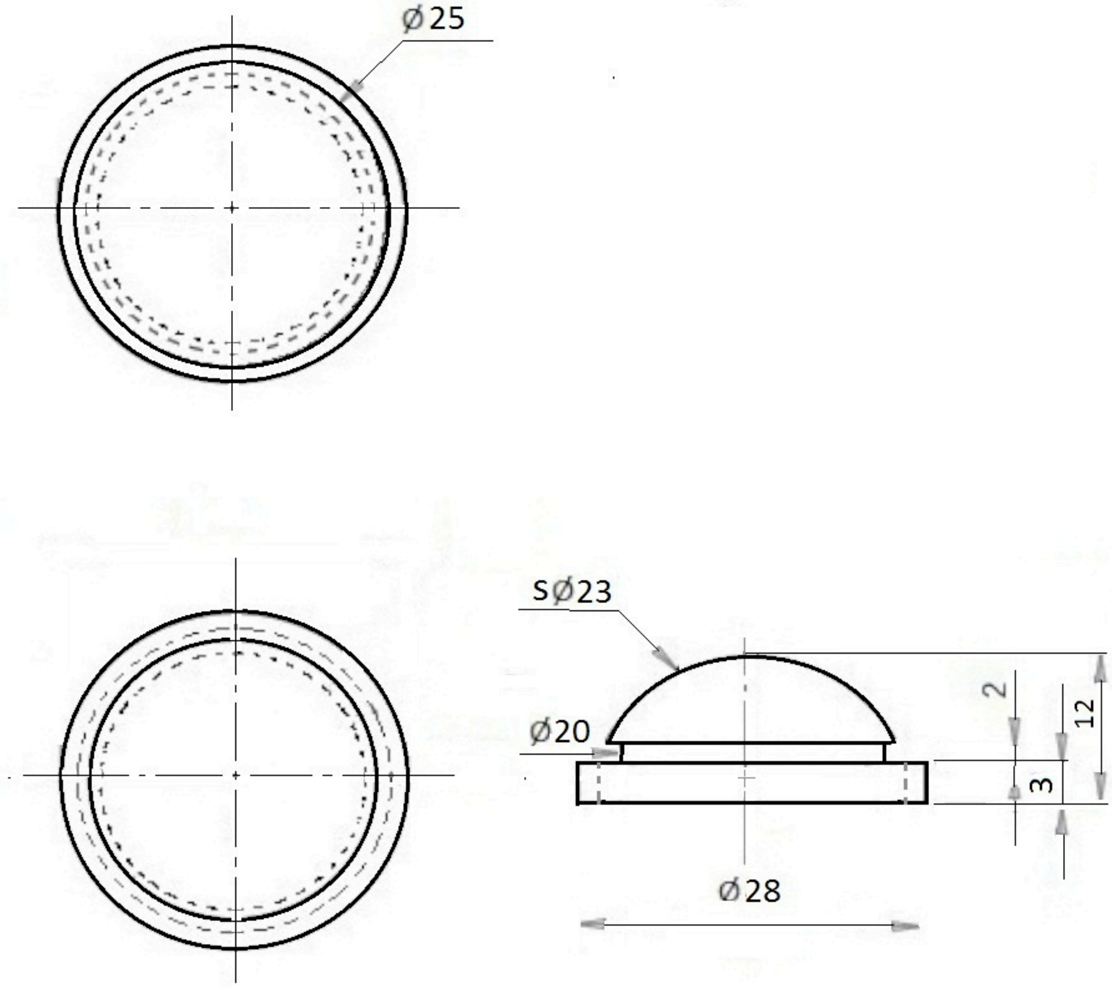
CHK. BY	DR. H.H			
SCALE 1.1	GLENOSPHERE			DRW NO 1.3

Appendix 4



REMOVE ALL SHARP EDGES AND BURRS
ALL FILLETS AND ROUNDS R3

	NAME	DATE	SIGN	EMU
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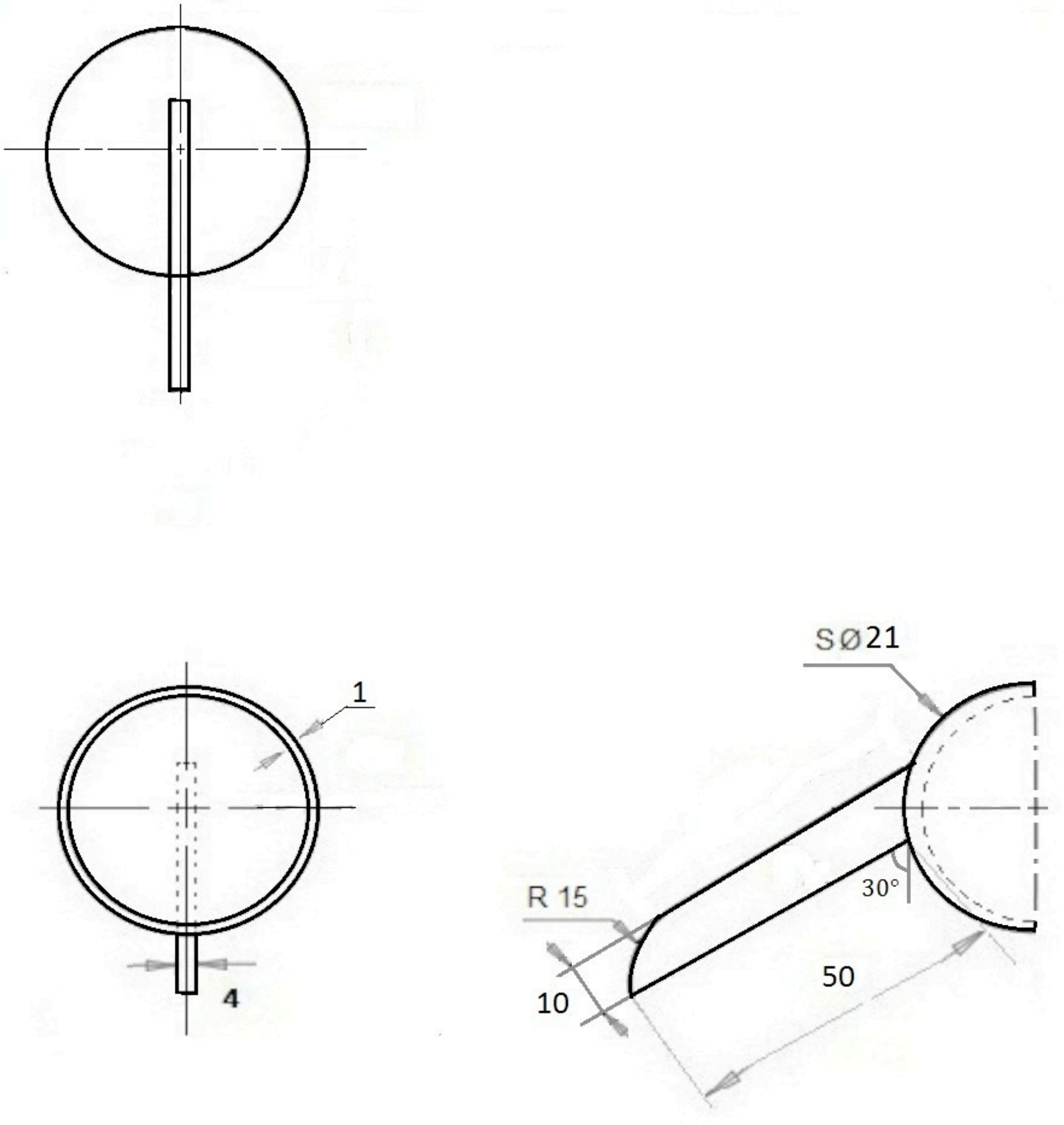
CHK. BY	DR. H.H			
SCALE 1.1	HUMERAL CUP			DRW NO 1.4

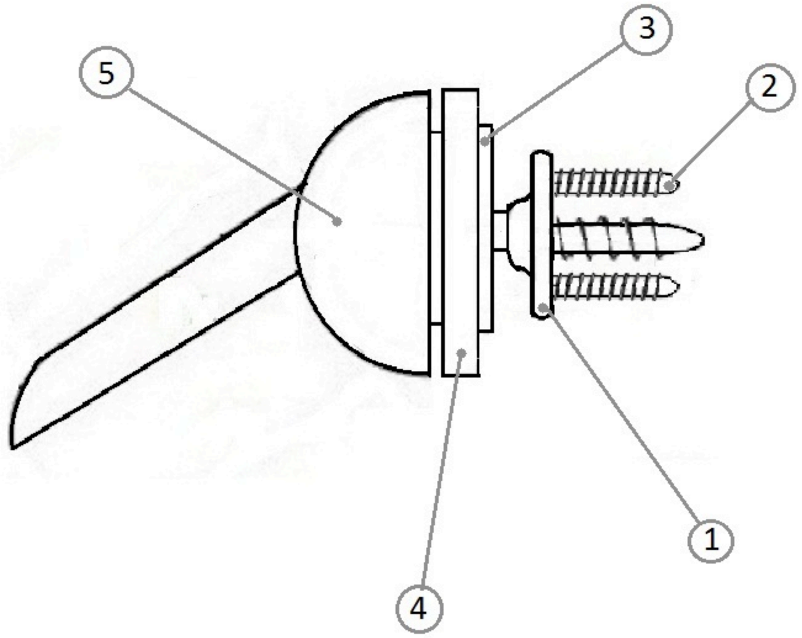
Appendix 5



REMOVE ALL SHARP EDGES AND BURRS
ALL FILLETS AND ROUNDS R3

	NAME	DATE	SIGN	EMU
DRW. BY	S.E	23.07.213		
CHK. BY	DR. H.H			
SCALE 1.1	HUMERAL STEM			DRW NO 1.5

Appendix 6



ITEM NO.	QTY.	ITEM NAME	MATERIAL
5	1	HUMERAL STEM	TITANIUM
4	1	HUMERAL CUP	POLYETHYLENE
3	1	GLENOSPHERE	TITANIUM
2	2	SCREW	TITANIUM
1	1	BASEPLATE	TITANIUM

	NAME	DATE	SIGN	EMU
DRW.BY	S.E	23.07.213		
CHK.BY	DR. H.H			
SCALE 1:10	REVERSE SHOULDER PROSTHESIS			DRW NO 1