Effect of Total Elbow Arthroplasty in Varus-Valgus Laxity and Stress Distribution of Elbow Joint

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ABSTRACT

Nowadays, there are vast number of studies, which concentrate on the elbow joint problems and total elbow arthroplasty (TEA). Mostly, these studies focus on the complications and failures of the implants. In this thesis the main objective is to understand how the varus-valgus laxity and stresses change when elbow joint is implanted as these may lead the failure and future problems of artificial joints. In this study varus-valgus laxity and Von Mises stress tests are performed. Varus-valgus laxity is measured during 140° of flexion motion with 15N and 50N loads for both anatomic and artificial elbow joint. Von Mises stress test is performed with a 15N load on the ulna of the anatomic elbow joint and ulnar part of the implant in artificial elbow joint.

In this thesis a 3D model of elbow joint implant has been designed and also 3D models of the ulna and humerus are used. These 3D models are assembled in order to create finite element (FE) models of anatomic and artificial elbow joints. Ligaments are neglected in order to decrease the time of the process.

Once the varus-valgus laxity and the Von Mises stress measurement tests are performed for the anatomic elbow joint, the same analyses are performed for implanted elbow joint. Obtained results from the FE model of anatomic and artificial elbow joints are compared with each other in order to understand the efficiency of the TEA and probable limitations, which may occur after total elbow replacement. As written in the literature review the implantation increases the varus-valgus laxity almost 20% in 140° of flexion motion. The maximum Von Mises stress of the implanted elbow joint is much higher than this value in normal elbow joint. The increase of the varus-valgus laxity is a cause of failure of the implants in TEA. Moreover, the increase in Von Mises stress leads to wear of the polyethylene part and finally failure of the implants.

Keywords: Total Elbow Arthroplasty, Range of Motion, Varus-Valgus Laxity, Von Mises Stress, Finite Element Analysis

ÖZ

Günümüzde dirsek eklemi problemlerine ve tam dirsek artroplastisine konsantre olan pek çok çalışma vardır. Bu çalışmaların çoğu dirsek implantlarının komplikasyonlarına ve bozulmalarına odaklanmıştır. Bu tez çalışmasının ana amacı, anatomik dirsek eklemi, yapay eklem implantları ile değiştirildiği zaman, yapay eklemdeki varus-valgus gevşemesinde ve stres sonuçlarında nasıl değişiklikler olduğunu tespit etmektir. Burada yapılan tez çalışmasında, yapay ve doğal dirsek eklemlerinin gevşekliği ve Von Mises stres analizleri yapılmıştır. Dirsek eklemlerinin gevşekliği ve Von Mises stresi, 15N ve 50N yükler kullanılarak, kolun 140^0 bükülme hareketi sırasında test edilmiştir.

Bu tezde üç boyutlu dirsek eklemi implantları tasarlanmış ve anatomik üst ile alt kol kemikleri (humerus,ulna) kullanılmıştır. Üç boyutlu eklem implantları ile anatomik kemik modelleri bir araya getirilmiş ve sonlu elemanlar analizinde kullanılmak üzere birleştirilmiştir. Analiz sürecini düşürmek için dirsek ekleminin lifleri analizde kullanılmamıştır.

Gevşeme ve Von Mises stres analizleri öncelikle anatomik dirsek eklemi için gerçekleştirilmiş, daha sonra da aynı işlemler yapay dirsek eklemi için uygulanmıştır. Anatomik ve yapay dirsek eklemleri için kullanılan sonlu elemanlar programı sonuçları birbirleri ile karşılaştırılmış. Yapılan karşılaştırmanın amacı tam dirsek artroplastisinin etkinliğini ve sınırlamalarını anlamaktır. Geçmiş çalışmalara bakıldığı zaman, yapay dirsek eklemlerindeki gevşemenin anatomik eklemlere oranla %20 arttığı yazılmıştır. Bunun yanında yine anatomik dirsek eklemi ile karşılaştırıldığı zaman Von Mises stres sonuçlarının yapay dirseklerde çok daha yüksek olduğu yazılmıştır. Bu olgular yapılan tez çalışmasında da desteklenmiştir. Yapılan çalışmadan da anlaşılacağı üzere, yapay dirsek ekleminde, stres ve gevşemedeki artış implantın polietilen parçasında aşınmaya ve ileri bozukluklara sebep olabilir.

Anahtar Kelimeler: Tam Dirsek Arthroplastisi, Hareket Alanı, Varus-Valgus Dirsek Gevşekliği, Von Mises Stes, Sonlu Elemanlar 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
TEA	Total Elbow Arthroplasty
TER	Total Elbow Replacement

Chapter 1

INTRODUCTION

1.1 Functional Anatomy of Elbow

The elbow is a complex joint that is assumed to work as a combination of a hinge joint. This complex joint consists of three bones. The distal part of humerus is the upper part of this hinge joint, and the proximal parts of the ulna and radius are the lower parts of the joint. Ligaments, cartilage, tendons and muscles surround the joint to support, stabilize and ease the movement. Elbow joint complex consists of ulna-humeral, radio-humeral and radio-ulnar joints.

In general, two types of movements are defined for the elbow joint. The first one is translational movement, consists of three different translational motions along three axes x, y and z. Translational motion along x-axis is called anterior-posterior motion, along y-axis is called medial-lateral motion and finally along z-axis is superior-inferior motion. The other range of motion is rotational motion, which is categorized into three groups as the translational motion. Rotational motion around x-axis is called as varus-valgus motion, around y-axis is called as flexion-extension and around z-axis is internal-external motion.

The ulna-humeral joint performs the main flexion-extension motion. On the other hand, the elbow joint also has the ability of rotation, which allows the hand to be rotated and it happens through radio-humeral joint. This movement is called pronation and supination. These motions can be influenced due to the dislocations and injuries of elbow or due to joint replacement. Therefore, excessive joint laxity may occur in either normal or artificial elbow joints. In general, this laxity is known as the varus-valgus laxity.

1.2 Elbow Joint Dislocation and Laxity

Commonly, one of the most dislocated major joint is the elbow joint. It is also the most common dislocated joint of children with a recorded average rate of 10-25% of all elbow injuries (Pooley, 2007). Elbow dislocation is approximately two times more common in males and normally happens around the age of 30. Elbow instability is also one of the most commonly occurred joint problems. Almost 40% of patients who suffer from the elbow instability are associated with sports, whereas 75% of elbow dislocation between young people occurs during sport activities (Trail, 1999).

Generally, elbow dislocations are uncommon and typically when a person falls on an outstretched hand, they occur. The impact force is sent along the bones to the elbow, when the hand hits the ground. Car accident can be another reason for elbow dislocations, for example due to the influences of the crash or when the passenger tries to prevent the impact.

The combination of the ligaments, muscles and bone surfaces stabilize the elbow. When an elbow is injured or dislocations occur, all or some of these parts can be injured. Totally, elbow dislocations can be classified in 2 major categories.

A simple dislocation is a commonly a lateral and posterior dislocation and does not have any associated fracture and major bone injury. The procedure to treat simple elbow dislocations is keeping the elbow immobile for a couple of weeks. The movement of the elbow may be affected and range of movement may be decreased, if the elbow be immobile for more than needed time of treatment.

A complex dislocation is an elbow dislocation with associated fracture and can have also ligament injuries. Surgery may be necessary to treat the injuries, repair the ligaments and restore bone alignment, in a complex elbow dislocation. Realigning of a complex elbow dislocation and keeping the joint in a proper condition is difficult. The elbow is protected and supported with an external hinge, after surgery. This device prevents the elbow from re-dislocating. Additional surgery may be required to treat the injuries, if the elbow dislocation is associated with nerve and blood vessel problems. Nerves and blood vessels, which are placed around the elbow, may be damaged, in the most severe dislocations.

Some individuals have a congenital abnormal and greater laxity in their ligaments. These people are in danger of a greater risk of elbow dislocation. It is proved that people, who have congenital shallow groove of the ulna bone, are at a slightly higher risk of dislocation.

A complete elbow dislocation is obvious and extremely painful. Furthermore, a complete dislocated elbow may have an unusual twist and will deform the arm. On the other hand, the detection of a partial elbow dislocation or subluxation is harder. Typically, a subluxation occurs after an accident. As the elbow is just partially dislocated, the normal movement of the bone can be continued and the joint may be apparently normal. However the elbow may usually move properly, nevertheless there may be pain. If the ligaments never heal, partial dislocations may continue to occur again over time. Therefore, after injury or joint replacement surgery the elbow joint laxity is tried to be tackled. However, after joint replacement normal joint articulation might not be achieved.

In a healthy elbow joint, the bones covered with a tough protective tissue called cartilage and the surfaces are very smooth. Various problems such as arthritis may cause damages to the cartilage and bone surfaces at the contact of three bones of the elbow joint. Eventually, painful problems occur due to the damaged surfaces and cartilages of elbow.

Total elbow replacement (TER) is a way to reduce some elbow pains. In TER surgery, an artificial hinge, which is made of plastic materials and special metal alloys, is placed into the joint so humerus and two forearm bones can move smoothly on each other.

Elbow joint dislocation and its relation with laxity have been studied by many researchers.

1.3 Elbow Joint Implants and Need in Elbow Joint Arthroplasty

Commonly, unlinked implants consist of two metal stems (ulnar stems and humeral stems). These parts are not mechanically jointed, and just slide smoothly on each other. A strong plastic material like UHMWPE minimizes the wear at the contact between the implant parts.

Linked elbow implants normally consist of two stems, which are made of metals that a metal locking pin connects them. The locking pin attaches the ends of stems that are covered with a strong plastic material.

Humeral stem is a part of elbow implant that is placed into the humerus during arthroplasty. Some medial and lateral fins are designed on the surface of the stem's pin to minimize intra medullar rotations. Ulnar stem is a component of the prosthesis, which is placed in ulna bone. Ulnar stem is available in two types short and standard. To improve cement fixation some notches have been designed. This stem also fined to prevent the rotation of the components inside the bone. The standard stem has the same geometry of the ulna; it is curved to simulate natural shape of the ulna and decreases the stresses.

Total elbow arthroplasty (TEA) has been recognized as a common method for treatment and medical care of arthritic elbow (Mori, 2006). As the number of patients who need primary TEA is increasing, progression of the technical demands is also necessary. The surgical procedures have many posterior problems, and these need to be improved. Different problems, such as major bone loss and further joint laxity, may occur after these procedures.

Robineau performed the first arthroplasty in 1927, and that was a distal humeral hemiarthroplasty. Earlier performed elbow arthroplasty was excisional. In the early stages, single axis hinge implants were used in total elbow arthroplasty.

Different methods can be used for reconstruction and treatment of bone defects and deformations in TEA. Several techniques have been mentioned and described as using custom long-stem and standard components, including impaction grafting, cortical strut allograft, an allograft-prosthesis composite and cancellous autograft (Ehrendorfer, 1999. Mansat, 2004. Peters, 2007).

Current implants can be generally classified into 3 groups; linked implants, which have physical connection between ulnar and humeral parts, unlinked implants, in which the components are not attached together and just smoothly move on each other, and finally those, which can be changed from unlinked to linked implants. Third group of implants are designed as unlinked but they have the ability to be converted to linked implants by using physical connections, for instance hinge and screws. The expressed groups can be categorized further in details. If there is varus-valgus rotation between ulnar and humeral parts, it is called sloppy hinge and if there is no rotation, it is called fixed hinge. In terms of function, the recorded results have proved that unlinked and sloppy hinge implants have shown better outcomes than the fixed hinges (Little, 2005).

One of the advantages of a linked implant when comparing with an unlinked implant is that linked implants are more stable due to connectivity of the components and it reduces the risk of loosening. However, in some papers it has been mentioned that the rates of loosening for sloppy hinge implants are lower than unlinked devices (Little, 2005).

1.4 Organization of the Thesis

This thesis consists of six chapters, the appendix and references. Chapter 1 contains introduction. In Chapter 2 literature survey is written and the results of various performed studies over different implants, failures, complications and joint laxity measuring instruments, are reviewed. In Chapter 3 a FE model of normal elbow is analyzed and afterwards a FE model of implanted elbow joint is analyzed. The results are demonstrated in 4th Chapter and the discussion is written in Chapter 5. Eventually, conclusion and suggestions for future works are presented in Chapter 6.

Chapter 2

LITERATURE SURVEY

2.1 Biomechanical Modeling of Elbow

Many researchers studied elbow joint and focused on elbow joint modeling. Mendoza J *et al*., (2009) modeled elbow a 3D joint. They simulated the mechanisms with parallel topology, which was consisted of universal joints and electric linear actuators, with 3 DOF. Their study is concentrated on kinematics and they assessed the elbow inverse kinematics by using MatLab and the ability of their mechanical elbow to replicate the biological elbow movements.

Scheepers F *et al*., (1997) represent a model of upper limb muscles. This model was developed to simulate the automatic reaction in the normal position of articulated skeleton. A procedural language was used in the implementation of models, in which the objective was ease of availability of the facilities for manipulating and defining articulated models. The muscles are automatically deformed after making changes in the position of the skeleton. An additional parameter has been considered to create the muscle tension.

Zhang *et al.,* (2008) performed an experimental study and they created and modified a 3D model based on human thorax. Upper limbs and muscles play a role as a part of a complex project, which is known as Mechanical Virtual Human of China (MVHC). They used that model to create dynamical and kinematical definitions that can be used for different situation and purposes in biomechanics.

Lan N *et al.,* (2001) constructed a 3D biomechanical model of the neuromuscular system of the human upper limb. The objective of their study was to develop a control system, which can be used in electrical stimulation of the upper limb muscles. An elbow model has been evaluated by MatLab in their study.

Bernabel R *et al.,* (2006) developed a skeleton model to describe the behavior of the forearm bones by using ANSYS. This model was developed and modified in order to improve the post-operative recovery of the patients after surgery of the forearm fractures.

Teran J *et al.,* (2005) represented a new FE algorithm, which decreased simulation times in the earlier modeling. Later, Blemker S *et al.,* (2005) performed a study to assess their algorithm to demonstrate the behavior of the skeletal muscles.

Teran J *et al.,* (2005) progressed a complex model for the human upper limb, which was shown to be applicable for different purposes. A group of the 30 most important muscles are considered in the developed model. The results had simulations with high resolution and for the muscle; isotropic crossing and quasi-incompressible elements were used to combine fields of passive and active muscle fibers. A similar model was developed at Technical University of Munich for assessment of the knee kinematics and properties and enable users to measure the stiffness and laxity in 6 DOF (Riener, 2004).

Daniela T *et al.,* (2010) performed an experimental study to create an algorithm for obtaining 3D models of the human elbow joint by using CT images. They evaluate elbow joint by using FE methods and their assessment contains bones, muscles and ligaments. They execute this study to achieve valuable objectives. It could be useful for future works such as improving and optimizing elbow devices and prostheses.

Willing R *et al.,* (2010) assessed the elbow cartilage mechanics in their study by using ABAQUS. This study considers the ability of a computational FE model, in which CT imaging is used, to predict contact mechanics of elbow cartilage. Their results proved that the changes in contact mechanics are predictable by using this model.

2.2 Elbow Joint Implant Production and Development

Nowadays various companies are producing elbow joint implants. However, they use different manufacturing procedures and materials, they follow the same aim. Different types of elbow implants are available, and they have been used to reconstruct the normal joint behavior.

Here, some types of implants from different companies are gathered. Capitellocondylar [Codman and Shurtleff, Randolf, MA], Coonrad-Morrey [Zimmer, Warsaw, IN], Souter-Strathclyde [Stryker Howmedica Osteonics, Limerick, Ireland], Discovery [Biomet, Warsaw, IN], Pritchard-Walker [DePuy], GSB III [Sulzer Orthopaedics, Alton, UK], Solar [Stryker, Mahwah, NJ], ERS [DePuy, Warsaw, IN], Norway [Brodrene Johnsen

AS, Norway], Sorbie [Wright Medical Technology, Arlington, TN], Kudo [Biomet Europe, Dordecht, The Netherlands].

Anthropometric evaluation has been affecting prosthetic designs. As a recommended case, canal analyses suggest tapered stems for the distal ulna (Gordon, 2002), where cylindrical humeral stems are more suitable for total shoulder arthroplasty (TSA) (Robertson, 2000). Currently, there is not enough information recorded, which shows the relationship between ulnar and humeral bone for total elbow arthroplasty.

Most of the available humeral stems are tapered gradually in varying degrees. Some of them taper just in the medial-lateral plane (Discovery, Coonrad-Morrey, ERS), some taper just in the anteroposterior plane (Kudo, Norway, Sorbie), and others taper in both planes (Pritchard-Walker, Solar, GSB III, Capitellocondylar, Souter-Strathclyde). In addition, the degree of taper can be changed based on the sizes of implants (Warsaw, 2001). Implants may be weak proximally as a cause of this tapered design. Furthermore, circumferential hoop stresses in the cement may lead implant loosening and fractures. This stress may occur during axial loading of a tapered stem or during polymerization (Stauffer, 1982). A cylindrical stem may decrease fracture rate of implant and would permit operation of a larger implant and stiffer stem. Many implant fractures have been reported in several performed studies (Kazak, 1998. Morrey, 1992).

McFarlane and Macdonald (1991) record that the diameter of the ulna canal is the largest proximally and reducing distally, so the optimal design for the ulnar should be tapered in all dimensions. However, different available brands of elbow implants have tapered ulnar stems. Some stems are tapered only in one dimension (Sorbie, Pritchard, Kudo). Stem diameter can be maximized along the ulnar shaft by a tapered ulnar stem, which has a same rate to the bone, and fracture resistance of the implant will be increased as a result. As the fracture of the ulnar stem is known as an elbow arthroplasty complication, this may have clinical justification (Connor, 1998. King, 1997. Ramsey, 1999). Furthermore, larger stems may be required for male patients for optimal fit in the canal, because it is recorded that the male canals are considerably larger than female canals in different sections.

One of the important factors in intraoperative and postoperative complications can be the cortical bone thickness of the ulnar and humeral canals. Fracture rate is increased when thinner cortices are used and also transmitted potential heat to the soft tissue is higher while cement removing and when one of them is in use (Gill, 1998. O'Driscoll, 1999). Where the canal and the cortex are the smallest, the possibility of the ulnar fracture and perforation is higher and increase distally (Connor, 1998).

2.2.1 Elbow Implant Failures and Complications

Levy *et al.,* (2009) performed a study about the differences of survival and failure rate in linked and unlinked implants and valuable results were achieved. Acceptable results of long-term survivorship are recorded for total elbow arthroplasty (TEA). Linked prostheses had a higher rate of survival than unlinked implants. Recorded data shows that a better rate of survival was achieved when an unlinked implant revised with linked implant.

Unlinked elbow implants were used for younger patients. The average age of 60 years is reported for patients treated with linked implants and 54 years for the unlinked implants. Long-term survival rates of TEA are supposed to be lower in younger patients (Talwalkar, 2005). This difference probably is because of the increase in need of young people to TEA.

Remarkable results have been recorded for the unlinked implants, which are replaced with the linked implants. Ring et al. noted that a low survival rate of 47% is recorded when unlinked implants are replaced with other unlinked implants (Levy, 2009).

Functional assessment represents differences between types of implants, where sloppy hinged implants had an excellent outcome (82%) and unlinked (78%) or fixed hinge prostheses (73%) had a lower rate. Unlinked implants showed a lower range of movement in comparison with linked components. (Little, 2005)

Implant failure is recorded for both unlinked and linked implant types, with a 4% average rate. Failure of the components was reported with different brands of implants, such as the Coonrad III (fracture of ulnar stem), the Baski (fracture of humeral stem), the Kudo 4 (fracture of humeral stem) and the Capitellocondylar (fracture of ulnar polyethylene) (Little, 2005). The components detachment in linked implants indicated failure of the axle locking mechanism or components disconnection. For the sloppy hinge the rate of 6% is recorded for components detachment and also 1% with fixed hinge implants. In a performed study, 23 Pritchard II sloppy hinge implants was reviewed and four of them had detached, in six of them with the locking mechanism axle seen to be backing out, but they are not considered as failure because they did not need functional fixation (Madsen, 1994).

Renfree *et al.,* (2004) treated 10 patients by using allograft-prosthesis composites. Remarkable results have been recorded for stability and pain relief. However, no acceptable functional outcome was reported. Four allograft-related failure happened, three of them had problem with the ulnar part. Mansat *et al.,* (2004) used the same prosthesis in 13 patients, deep infection happened for four patients and that cause implant removal in three of them, even good results were achieved in 9 other cases.

Most of the performed studies have often been involved in the development of prostheses. Furthermore, results are often evaluated by using different endpoints. Pain relief is obtained in most of the patients and perseveres long term (Little, 2005). There has been one paper, which stated that the incidence of pain at rest may increase with time but this did not consider statistical results (Van Der Lugt, 2004).

The range of motion mostly improves after arthroplasty. Little *et al.,* (2005) found that range of motion is considerably higher in patients treated for post-traumatic arthritis compared with patients treated for rheumatoid arthritis.

Most of the performed studies consider the results in patients who suffered from rheumatoid arthritis, and ulnar loosening. The rate of ulnar loosening has been reviewed; and remarkable difference between uncemented components and cemented components found. The rate of ulnar loosening with uncemented components is higher than cemented components (Van Der Heide, 2007. Brinkman, 2007). Linked implant components have been suggested to be used in rheumatoid arthritis due to the related ligament laxity and bone loss. Most studies obtained acceptable outcome with the Kudo prosthesis (unlinked) even while considering gross deformity (Mori, 2006). Where the Souter-Strathclyde, Kudo and Coonrad-Morrey implants have been compared, there was better outcome with the Coonrad-Morrey prosthesis in terms of recovery and radiographic signs of loosening during 5 years. These results have been obtained from patients suffering from rheumatoid arthritis (Little, 2005). This implant has a remarkable rate of focal osteolysis of the ulnar component but the long-term effects of the implant are unknown. When arthroplasty is performed, the age of the patients for inflammatory polyarthropathy at the surgery time does not seem to have any effect on outcome (Talwalkar, 2005).

The largest elbow arthroplasty study for post-traumatic osteoarthritis was performed by Schneeberger *et al.* (1997). Forty-one patients were issued during 5 years. Patients' satisfaction was acceptable but there was a large extent of complications between patients and they needed further surgery. Mechanical failure of the prostheses was a problem for six patients and it forced them to have revision surgery. Four of them involved fracture of the ulnar component. Long term follow up data are necessary, although patients' satisfaction was acceptable during 5 years, because the demand have been increasing upon the prostheses by this patient group.

The complication rate of osteoarthritis is higher than inflammatory arthritis. However, there are acceptable results in elbow arthroplasty for osteoarthritis (Gregory, 2008).

The definitions of loosening are different from each other in the literature and it is a cause of differences between obtained results. Little *et al.,* (2005) described component migration as a definition for loosening, radiolucency of 2 mm or any radiolucency, which is in the same time with any kind of loosening symptoms. The average of loosening rate during a period of approximately 5 years was 9%. They compared loosening between linked implants and unlinked fixed-hinge and sloppy-hinge implants, where the linked implant loosening rate (5%) was lower than unlinked fixed-hinged implants (11%) and sloppy-hinge implants (10%). Higher loosening rates were observed in patients who treated for rheumatoid arthritis rather than other symptoms. When the definition of loosening is changed and it is known as radiolucency higher than 1 mm, then the differences between results appear. Totally, the loosening rate for linked sloppy-hinge implants is 15% and for fixed-hinges is 23% and for unlinked implants is 10%. Consequently, loosening was a more common symptom that was observed in patients treated for post-traumatic arthritis with fixed-hinge implants (Gregory, 2008).

Based on the performed studies, the deep infection rate after total elbow arthroplasty (TEA) is demonstrated to be approximately 4%. Post-operative wound problems are seen in approximately 8% of patients. However, there is a great risk in wound problems if the arm is not immobilized after the surgical operation. The wound problem rate is about 6% for immobilization more than nine days, where it is approximately 10% for only two days immobilization (Gregory, 2008).

Instability is defined as a great dislocation of the radiographic signs of disassembly/breakage or partial dislocation of a component or the implant itself. The recorded rate of instability for unlinked implants is 6%, while this value for linked implants is approximately 1%.

By a performed study in 2005, Little CP *et al.,* recorded that ulnar nerve problems were found in 5% of patients. In the literature, it has been reported that the ulnar nerve abnormality occurs with 2% average incidence. However, these are not the cases, which have been approved by nerve conduction studies. The ulnar nerve preoperative state is recorded by just 15% of the performed studies. Many patients that are involved with a higher risk of ulnar nerve abnormality e.g. mononeuritis multiplex, are suffering from RA. However, the need of revision surgery is a valuable decision, there is not any sufficient document for supporting normal transposition of the ulnar nerve.

Triceps problems are not considered in many performed studies. Re-operation rate of 2% is recorded for triceps problems (Celli, 2005). Little mentioned a rate of 3% in their performed meta-analysis (2005). Triceps insufficiency rate is related to the method used. The highest rate was seen when the triceps was totally detached (11%), although the triceps turndown showed the lowest rate (2%).

Pulmonary embolism is an unusual problem, which the rate of 0.0028% is recorded for patients after total elbow arthroplasty both with primary and revision surgeries (Dunkan, 2007). The mortality rate of 1441 patients who had undergone primary or revision elbow arthroplasty was 0.62% after 90 days (Sanchez, 2007).

2.2.2 Revision Elbow Arthroplasty

Periprosthetic infection and aseptic loosening are the most common cause for revision elbow arthroplasty (Morrey, 1987). The most common symptom for surgery is humeral implant loosening and sometimes ulnar loosening. The bone cortex breech is the most routine operative problem during cement removal for the cemented elbow implants (24%). That was approximately the same incidence for the ulna and the humerus. The 55% of good results have been recorded for patients who had revision surgery, where the available data for poor results is 45%. Some complications such as poor range of movement, further loosening and pain were recorded as reasons for poor results. Only 40% of patients, who had more than one revision procedure, had no problems related to their revision surgery.

There is a published revision surgery results from the Mayo clinic by Later King *et al.,* (1997) that is based on the Coonrad-Morrey prosthesis. The most common symptom of revision was aseptic loosening. This result was obtained from forty-one patients that were reviewed during approximately 6 years. No periprosthetic infection was observed in this series. Fracture or cortical perforation at the time of revision was seen in fourteen patients, and three of them caused radial nerve injury. No post-operative infection was recorded. Mild discomfort was seen in sixteen patients and twenty-two of them had total pain relief.

Souter-Strathclyde prosthesis recorded acceptable results in revision surgery but the complication rate was higher (Redfern, 2001). Two cases of periprosthetic infection were seen in a series of fifty patients which reviewed during 53 months after revision surgery and most of them undergone revision surgery because of aseptic loosening. However, an acceptable range of movement and pain relief were achieved, nevertheless eight patients required further surgeries and thirty percent had been involved with some complications. Two more patients involved periprosthetic infection and two repeated infection were reported.

Revision arthroplasty for infection was not considered in many performed studies. Periprosthetic infection forced 1.9% of a series of 305 patients who undergone primary arthroplasty to have revision surgery (Gille, 2006).

One of the probable problems in revision surgery is severe bone loss. Coonrad-Morrey prosthesis and an allograft strut were applied on 21 patients who were suffering from massive proximal ulnar bone loss (Kamineni, 2004). An acceptable level of graft incorporation was obtained in most cases, which the pain and function progression were noted during 4 years. Also, during revision surgery that complicated by massive bone loss, to restore bone stock, Impaction bone grafting has been used. That has been performed without or with the addition of strut allograft augmentation (Loebenberg, 2005. Tsidiris, 2004). Twelve elbow arthroplasty was performed with revision surgery and impacting bone grafting during five years. However 8 arthroplasty results was acceptable and treated patients were satisfied, nevertheless 6 cases required further surgeries.

Acceptable levels of pain relief, stabilized elbow and an improved range of movement can be provided by total elbow arthroplasty. The most common reason of failure is component loosening. However, there is not any clear evidence to prove that either unlinked or linked prosthesis is more related to loosening.

2.3 Design of Elbow Joint Implants

2.3.1 Implant Materials

Materials used to produce orthopedic implants differ depending on the production companies. Many various implant materials are available, although there is no particular material to be compatible for all patients and implants. Materials that are used to produce an implant depend on the design and special use of the implant. Also materials should withstand applied forces from daily activity and chemical environment in the body.

Implants are designed for different conditions; they can be used to help fracture recovery or joint replacement. An implant must be flexible, strong, and resistant to wear. However, the most flexible or the strongest material may not be the best material to be used. The ideal implant material is a material with the highest similarity of the physical characteristics and properties to the bone.

Although the physical properties of the materials are important, characteristics are important as well. The biological influences of the material on the body are also important.

Metals and a kind of plastic called polyethylene are the most common materials used in orthopaedic implants. A combination of these materials is used in most implant manufacturing. Different parts of metal and plastic components rub together smoothly with the minimum wear.

Most of the metal parts of implants are made from a mixture of two or more materials called alloy. Desired properties and characteristics are achieved by combining various metals. Stainless steel, titanium alloys and cobalt-chromium alloys are the most common alloys used in implant manufacturing.

2.3.1.1 Metals

Stainless steel is mostly used in implants that is mainly used for fracture repair. It is used as bone screws, plates, rods and pins. Commonly, this material is made of a mixture of iron with some other metals like molybdenum or chromium to improve the corrosion resistance. Normally, when resistance of an implant to the human body chemicals is considered, stainless steel is commonly used.

These alloys can be used in different types of joint replacement implants. A high percentage of cobalt and chromium is used in cobalt-chromium alloys, although other metals such as molybdenum is added to increase the corrosion resistance and strength.

The most flexible orthopedic alloys are titanium alloys. On the other hand they have lighter weight comparing with other alloys. Also they contain varying degrees of some other metals like vanadium and aluminum.

Commercially Pure (CP) titanium is used in some implants for special purposes such as making fiber metal. In this case a metal fiber layer bonded to the surfaces of prosthesis parts to allow cement to flow in the implant or make growing of the bone into the implant easier, for a better grip.

A material that is used for its corrosion resistance, biocompatibility and flexibility is tantalum, as it is a pure metal with remarkable characteristics and physical properties.

Trabecular Metal (TM) material is obtained from tantalum over carbon and has the same structure of the bone. The surface of this material has small pores, which the growing tissues can place into these pores and stand the implant to the right position.

2.3.1.2 Non Metals

Ultra High Molecular Weight Polyethylene (UHMWPE) is a kind of plastic, which is the most commonly used material for surface of prostheses. It is supposed to contribute in joint contact. In fact, this type of polyethylene is a special type of medical-grade, which was developed particularly for use in orthopaedic prostheses. When there is a movement of an implant metal part on the surface of the polyethylene, this material act as an extremely smooth layer and makes the wear minimal. Produced polyethylene would be more resistant to wear through a process called crosslinking. In this process, chemical bonds between the molecular chains become stronger. The percentage of crosslinking depends on the prosthesis type, as different degree of crosslinking is required for different purpose of implant.

Normally, ceramic materials are obtained from pressing and heating some metal oxides, like zirconium oxides and aluminum oxides, until they reach desired hardness and density. These materials are hard, resistant to corrosion, and biocompatible. Commonly, they are used in the parts of implant where there is no need of flexibility.

Composite materials are made from a mixture of two or more different materials without any chemical reaction between them. In fact, materials combined to develop physical properties to the desired characteristics. Ceramics and metal alloys are not categorized in the composite materials group as they include chemical bonding between their ingredients.

Bioabsorbable materials will be absorbed when their responsibility is finished in the body. These materials are biocompatible plastics that can be solved by normal fluids in the body. Some bioabsorbable sutures are available for use in surgeries. These materials may be used in implants for a special purpose i.e. reattaching soft tissue to bone.

Silicone is a flexible rubbery material. The implants made by silicone, mostly is used in the replacement of the toes joints.

2.3.2 Quality Control

Always, quality control of the materials and equipment is required in industry to demonstrate longevity and safety of the manufactured products. And when it is considered in medical facilities and products, it is much more important, because it must ensure the patients health and prevent them from paying more costs.

It is not possible to test medical products like prosthesis easily, because the simulation of all the movements of natural joints is difficult. Furthermore implants are supposed to work properly for a long time and it is not easy to test the prototype for a long period neither. On the other hand, the simulation of the surrounding environment of the joint is not simply executable, as obtaining the human body alternate lubricating fluid is difficult. Therefore, here modeling of the joints is proven to be the most reliable way of quality control.

2.4 Development of Joint Laxity Measuring Devices and Instruments

Sufficient methods are required to measure the range of motion of different human body joints. An ideal scoring system for hypermobility is a system that can be used in a simple way for a large number of various joints in epidemiological studies. Latterly, researchers and designers have developed mechanical devices for measuring the joint movements and laxity accurately.

Carter and Wilkinson (1964) devised the first scoring system and found that helpful for performing their work, which was on congenital dislocation of the hip.

Kirk *et al.,* (1967) have suggested a complex evaluation, but unfortunately it has been too much time-consuming experimentally for normal use. Beighton and Horan (1969) modified the Carter and Wilkinson`s system for testing and quantifying the joint laxity in patients who were suffering from the Ehlers–Danlos syndrome (EDS). This system had been modified by Grahame and Jenkins (1972) to cover passive dorsiflexion of the ankle more than 15°. Eventually, the 1969 system has been improved by Beighton *et al.,*

(1973) to be used in an epidemiological survey, which was about bone and joint disorders.

A performed study on 502 normal adults of South Africans indicates that the elderly people had a lower level of laxity than young population. Afterwards another scoring system was progressed. Poul and Fait (1986) have evaluated a performed work by JP Contompasis in detail, and described that as a more complex system than Beighton's modification of the Carter and Wilkinson's.

Bulbena and colleagues (1992) performed a study to assess Beighton system, and find the performance of this system in comparison with other systems. In this study Beighton's modification is compared with the most popular system in France and the original Carter and Wilkinson system.

The simplest facility for quantifying the range of movement is hinge goniometer. This device has some disadvantages, which decrease the measurement accuracy. The main problem is difficult positioning. The first goniometer was the Loebl hydrogoniometer. One of the most common goniometer that is currently produced is the MIE clinical goniometer (Loebl, 1967).

Myrin goniometer is a recent designed device. However, this goniometer is one of the recent modifications, which is similar to aircraft gyrocompass, nevertheless this instrument has some problems, for example, lack of the sensitivity, expensive price and the same accuracy of the simpler device.

Some additional devices have been added to improve the efficiency of the late instrument, which quantify the range of movement, for more sophisticated measurement. An electromagnetic movement sensor has been devised as modification for the shoulder (Johnson, 1996). Measurement instrument for the range of movement have been modified with a plurimeter and validated, for the hip joint and particularly it is suitable for use in primary care (Croft, 1996).

Photography is the used method by Troup *et al.,* (1968) for evaluating movement of the hips and lumbar spine in a sagittal plane.

Haskard and Silman (1985) modified fixed-torque screwdrivers, which quantify lower limb and forearm rotation. One such device is used for forearm rotation measurement and another for leg rotation. Fairbank *et al.,* (1984) modified a goniometric, in which six joints are considered.

The metacarpophalangeal (MCP) joint shape a part of conventional scoring system and the accessibility to this joint is not difficult. A radiological method is modified by Harris and Joseph (1949) for quantifying the range of extension at the MCP joint and a mechanism is improved by Loebl (1972) for abducting the fingers to evaluate movement at the MCP joints.

Lately, an electronic gravity goniometer has been modified by applying preset fixed torques for investigating the passive range of movement of the four MCP joints (Wagner, 1984). A progression on the hyperextensometer is represented by this method.

Also the arthrograph has been reconsidered and modified with a microprocessor-controlled arthrograph to provide better accuracy.

Silman *et al.,* (1986) have accepted the Gaussian distribution in joint mobility, which the fixed-torque instrument is a device for measuring that.

Fairbank *et al.,* (1984) performed an assessment and evaluate a group of 446 normal young people by using goniometry at 6 different joints. However, a weak outcome is reported, nevertheless significant connection between the range of movement at different joints has been found, except for elbow hyperextension.

Currently, the scoring systems, which have been used for hyperlaxity, have been developed specially for this demand, and it is not particularly suitable to be used in evaluation of joint hypolaxity (Bird, 1983).

Morrey and Chao (1981) used electronic goniometer to measure forearm rotation and elbow flexion. Also, they published their work of evaluating elbow joint by use of biplanar roentgenograms (1976) and concluded three-dimensional kinematics of the elbow joint. Tanaka *et al.,* (1998) achieved the first three-dimensional elbow kinematic by using electromagnetic motion tracking data. Bottlang *et al.,* (2000) traced the dynamic and passive movement of the normal elbow joint by using direct electromagnetic motion tracking. Recently, Arashidi *et al.,* (2010) used the Stewart platform based devices for assessing the forearm motion, and acceptable results is recorded. While the technology is progressing, magnetic sensors have been applied to human joint measuring instruments (cutti, 2008).

It is realized that none of the devices can be extremely efficient to be used for measuring range of motion and laxity of neither anatomic nor artificial joints. Therefore, the modeling is shown as an effective method to analyze range of motion and laxity of anatomic joints.

Chapter 3

MATERIALS AND METHODS

3.1 Designing of 3D Finite Element Models

In this thesis different computer software are used to create 3D models of bone and implant parts. SolidWorks® and Geomagic® are used to create and manipulate the implant parts. Also ANSYS® is used to perform FE analysis.

3.1.1 3D Models of Humerus and Ulna

Bone files, which mostly are obtained from CT Scan or MRI, inserted into Geomagic® software and bone surfaces modified and manipulated. (Figure 3.1 and 3.2)

Figure 3.1: Humerus Bone

Figure 3.2: Ulna Bone

3.1.2 The Humeral Component of the Elbow Implant

For this part of implant, a cylinder with specific dimensions is created. This cylinder plays an important role in movement of the hinge joint. Afterwards, a pin is created as humeral stem and is attached to the cylinder. This pin is designed to place and fix in the humerus and to prepare the stability of the component (Figure 3.3). Dimensions are given in Appendix 1.

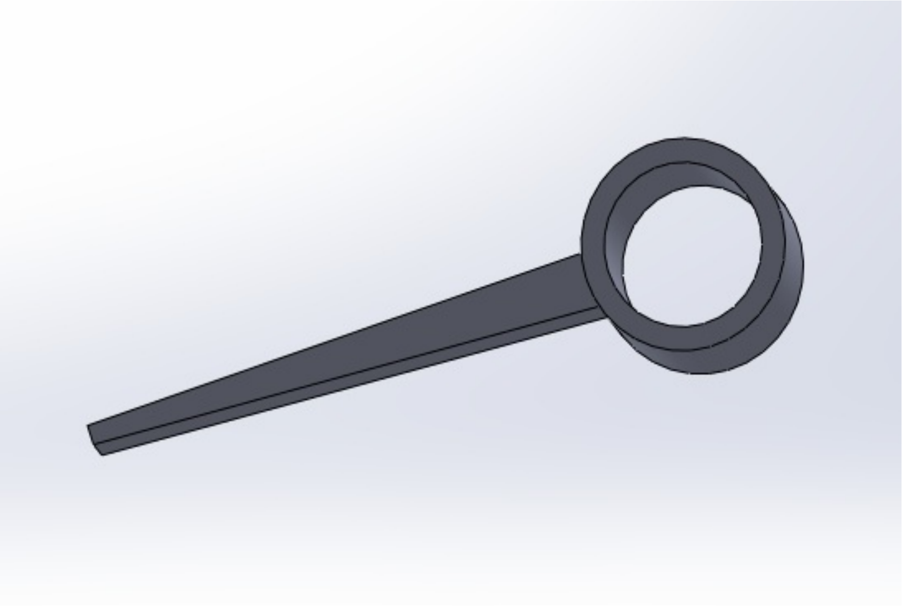

Figure 3.3: The Humeral Part of the Elbow Implant

3.1.3 The Ulnar Component of the Elbow Implant

To create the ulnar part of the implant in SolidWorks®, another cylinder was designed, and then an extruded cut was performed on the cylinder from the center to create a half cylinder. Afterwards, a pin, which is demonstrated in the appendix 2, was created and connected to the half cylinder to create the ulnar stem (Figure 3.4). As the ulna is thinner than humerus, the ulnar pin requires a more accurate design to protect the ulna against the force concentration.

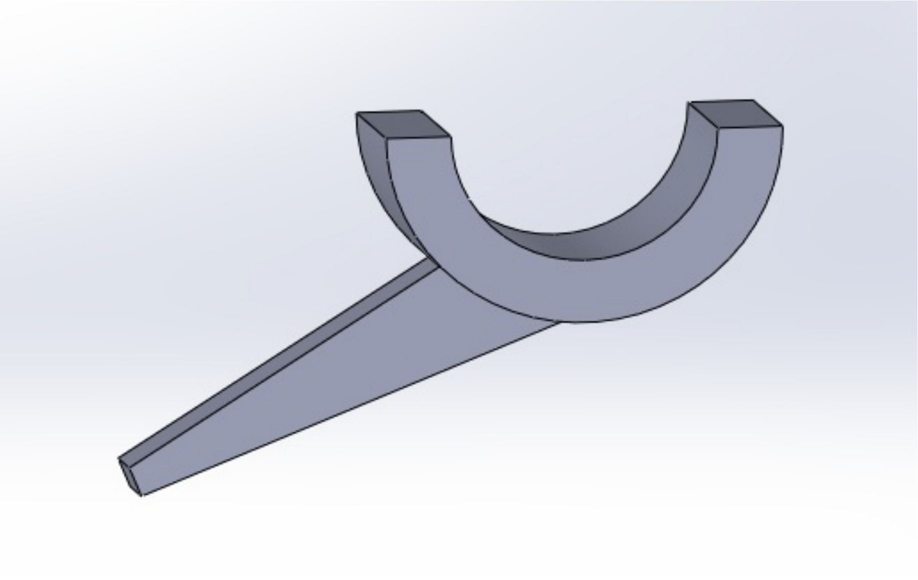

Figure 3.4: The Ulnar Part of the Elbow Implant

3.1.4 Ulnar Cup

To create the ulnar cup a very thin layer of a half cylinder is designed with the dimensions (width and radius) of the ulnar cylindrical part to place in the inner side of the half cylinder (Figure 3.5)

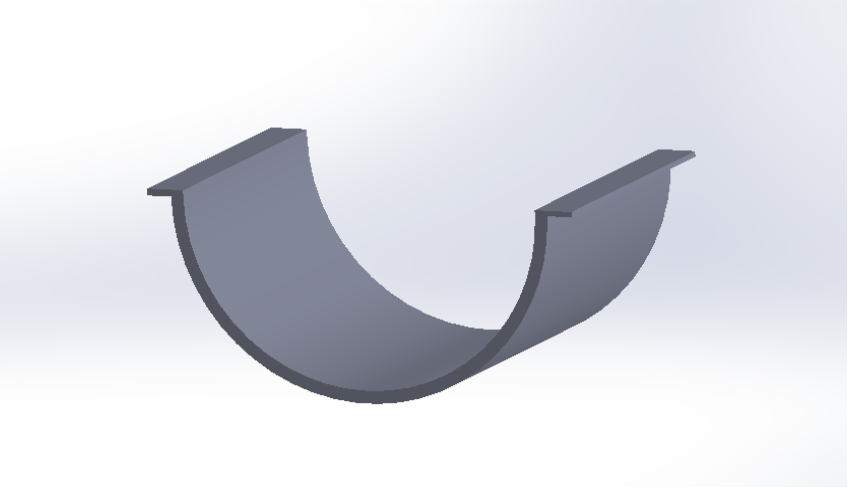

Figure 3.5: Ulnar Cup

When the two parts of the implant are assembled in the bones, these component need to be mated to complete artificial elbow joint and prepare for the FEA.

3.2 FE Modeling of Anatomic Elbow Joint

For the analysis of anatomic elbow joint, just the humerus and the ulna are used and inserted into ANSYS program (Figure 3.6). Ligaments are neglected in the analyses to reduce the processing time. As one of the main problems occurs in artificial joints is excessive stress occurs at joint contact, therefore FE model of anatomic and artificial elbow joint have been created and Von Mises stresses have been obtained.

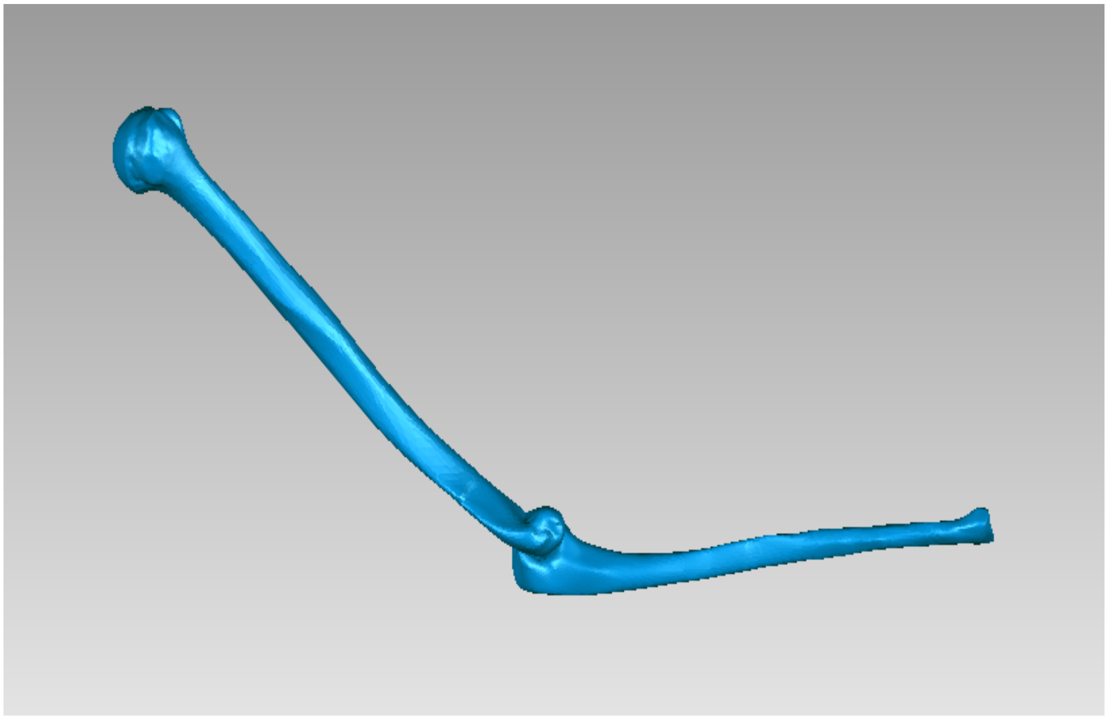

Figure 3.6: Assembly of Anatomic Elbow Joint

3.2.1 Material Properties of Anatomic Elbow Joint Parts

Material properties of bone are considered for the humerus and the ulna, and inserted into the ANSYS (Table 3.1). Two bony parts of the anatomic elbow model are assumed as linear elastic, viscoelastic and isotropic materials. Required parameters, such as Bulk modulus (K), Shear modulus (G), Young's modulus (E) and Poisson's ration (υ) can be driven from equations (3.1) to (3.12). These properties are assumed for Von Mises stress test and bones were modeled as rigid bodies for the laxity measurements.

3.3 FE Modeling of Artificial Elbow Joint with Implant Parts

For the analysis of the artificial elbow joint, the designed components of the implants are assembled into the bones and then all the parts are inserted in ANSYS software for the analysis (Figure 3.7). This model is prepared for Von Mises stress test and varus-valgus laxity measurements.

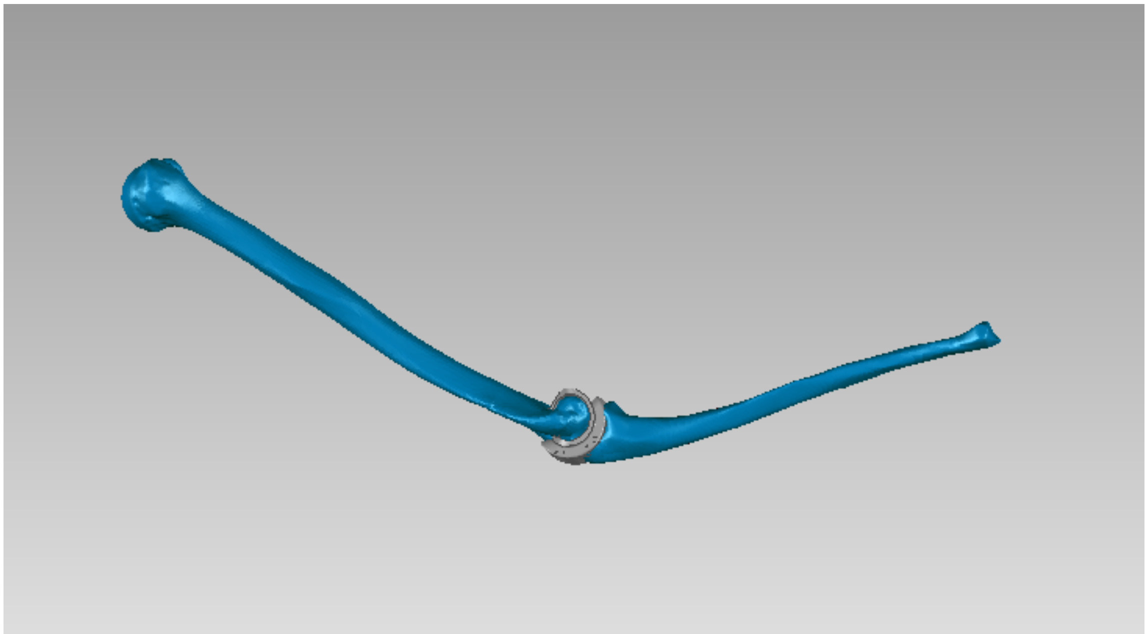

Figure 3.7: Assembly of Elbow Joint with Implant Parts

3.3.1 Material Properties of Artificial Elbow Joint Parts

It is obtained from the literature that the metallic parts of implant are made of titanium alloy and a layer of a specific plastic, which is called UHMWPE. Components are assumed as linear elastic, viscoelastic and isotropic materials. Elasticity parameters, such as Bulk modulus (K), Shear modulus (G), Young's modulus (E) and Poisson's ration (υ) will be achieved from equations (3.1) to (3.12). Material properties of different parts of artificial elbow model are represented in Table 3.1. These properties are used for evaluation of Von Mises stress, although all the parts of the assembly are assumed as rigid bodies for the varus-valgus laxity measurements.

The relationship between Bulk modulus (K), Shear modulus (G), Young's modulus (E) and Poisson's ratio (υ) are shown as follows.

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:

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

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

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

Table 3.1: Materials Properties of Anatomic and Artificial Elbow Joints Parts

Properties	Unit	Bone	Titanium alloy	UHMWPE	Cartilage
Density	$\mathrm{Kg\ m^{-3}}$	2100	4430	950	1050
Shear modulus	Pa	5.4615E+09	4.2399E+10	3.8732E+08	1.77E+05
Bulk modulus	Pa	1.1833E+10	1.2004E+11	2.2917E+09	2.16E+06
Elastic modulus	Pa	1.42E+10	1.138E+11	1.1E+09	5.18E+05
Poison ratio	–	0.3	0.342	0.42	0.46
Tensile yield strength	Pa	1.14E+08	8.8E+08	2.5E+07	1.2E+07
Compressive yield strength	Pa	1.20E+08	9.7E+08	1.4E+07	3.57E+07

3.4 FE Analyses of Anatomic and Artificial Elbow Joints

In this thesis, ANSYS Workbench is used to analyze anatomic and artificial elbow joint models. In the first step of each part of analysis, the prepared elbow models, which are explained in the previous sections, are used.

3.4.1 Meshing

The most important part of the analysis when performing FEA, is meshing. In this step, the model is divided to various elements in order to partially calculate the variables and then the main result will be achieved from the partial outcomes. Meshing has a large effect on accuracy of the results. A coarse mesh will influence the accuracy of the results, for example it can increase the time of the process, CPU usage and etc. Eventually, it will cost energy, money and time. There are different ways to solve the meshing problems, for instance, omitting the sharp edges.

3.4.2 Von Mises Stress Analysis

In this part of analysis all the materials properties are inserted into ANSYS. Some of the properties were defined as defaults in ANSYS, but the others are inserted manually in ANSYS Material Library. Joints and contacts are defined. Humerus is considered as the fixed part. Spherical joint is defined between ulna and humerus in anatomic elbow joint and between two parts of the implant in artificial elbow joint. 140° of flexion (Figure 3.8) is defined for movement of the ulna and the analysis is assumed to be performed during 4 seconds. Tetrahedrons meshing with path independent algorithm are considered for all parts. Frictionless contacts are defined between ulna and humerus in the anatomic joint and between two parts of the implant in the artificial joint. A normal load approximately equal to the weights of forearm and hand (15N) is applied for the flexion. Once Von Mises stress is evaluated on ulna in anatomic elbow joint and on ulnar part of the implant in artificial elbow joint.

3.4.3 Laxity Measurement

All the elbow joint components are considered as rigid bodies for laxity measurement. Humerus is defined as the fixed component and the ulnar part rotates around the humerus head with 2 DOF. Frictionless contacts are considered between ulna and humerus for the anatomic elbow joint and between two parts of the implant for artificial elbow joint. Once a normal load approximately equal to the weight of forearm and hand (15N) is applied to the center of mass of the ulna in the direction of varus (Figure 3.9) and the degree of laxity in this direction is measured during elbow flexion (Figure 3.8). Afterwards, direction of the load has changed to the valgus direction (Figure 3.9) and laxity is measured during the flexion. This procedure has been repeated for measuring the varus-valgus laxity for implanted elbow joint as well. Also, all the analyses have been performed for anatomic and artificial joint with a 50N load.

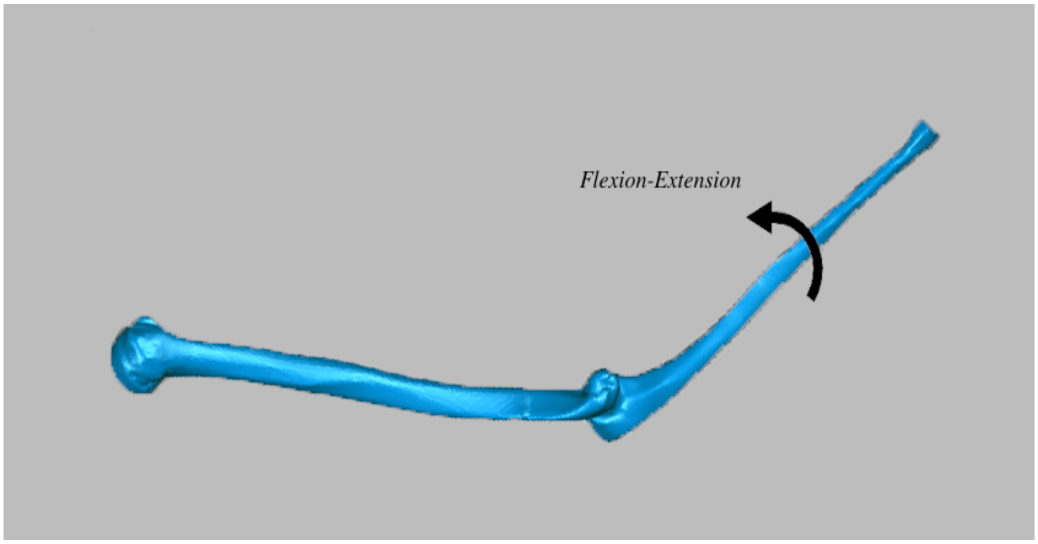

Figure 3.8: Flexion-Extension Motion

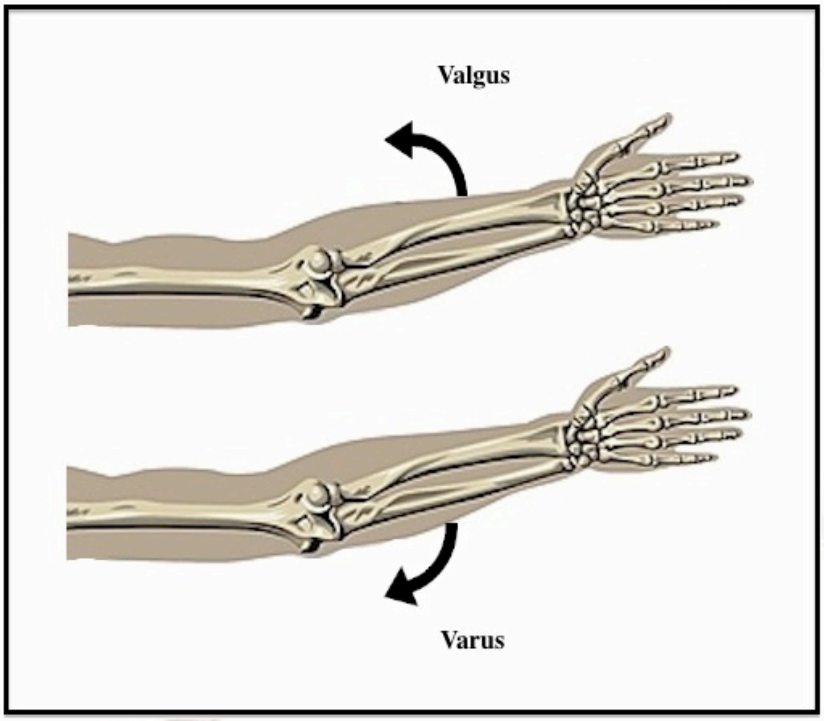

Figure 3.9: Varus and Valgus Directions

Chapter 4

RESULTS

Elbow problems, which may lead to elbow arthroplasty, may occur in all the individuals that influence the activities of daily living. In this thesis Von Mises maximum stress and varus-valgus laxity of anatomic and artificial elbow joint are analyzed and results are demonstrated to represent the post-operative limitation, problems and influences of elbow arthroplasty. FE analysis is conducted and the outcomes show the need of improvement of the implants to bring the highest percentages of the satisfactory for the patients, who undergone TEA. In this analysis the joint parameters, once are assessed and calculated for the anatomic elbow joint and the same procedures are performed for the implanted elbow joint as well. The obtained results from the analysis of anatomic and artificial elbow joint are compared in the chapter 5 to show the need of improvement of elbow implants.

4.1 FE Analysis of Anatomic Elbow Joint

4.1.1 Von Mises Stress

Maximum Von Mises stress results on the ulna of an applied load (15N) to the forearm for the flexion are given in Table 4.1 and in Figure 4.1.

Table 4.1: Maximum Von Mises Stress on the Ulna of Anatomic Elbow Joint

Time (s)	Max Stress (MPa)
0.4	13.731
0.8	12.134
1.2	12.765
1.6	12.857
2	14.187
2.4	13.392
2.8	14.061
3.2	14.738
3.6	14.643
4	15.359

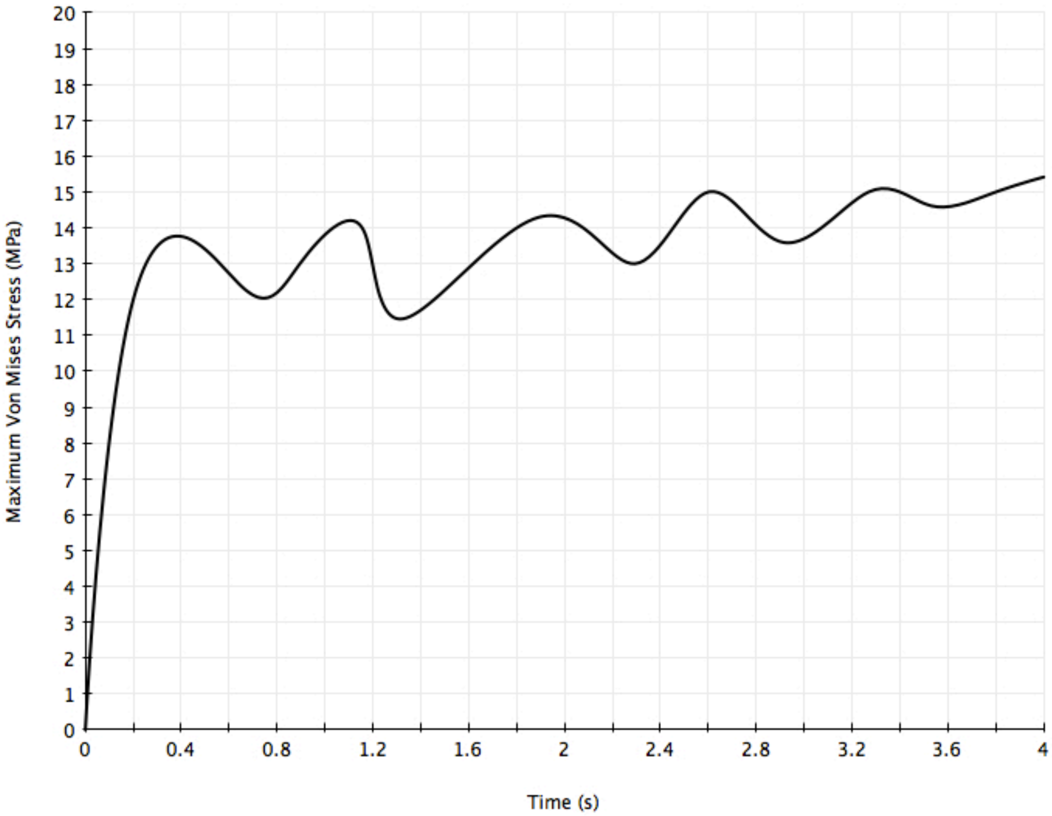

Figure 4.1: Maximum Von Mises Stress on the Ulna of Anatomic Elbow Joint

4.1.2 Varus-Valgus Laxity Measurement

4.1.2.1 Laxity Measurement with 15N Load

The results of Varus-Valgus laxity with a load approximately equal to the weight on forearm (15N) are given in the Table 4.2 and demonstrated in Figure 4.2.

Table 4.2: 15N Loaded Anatomic Elbow Joint and Varus-Valgus Laxity

Flexion (Deg)	Varus (Deg)	Valgus (Deg)
10	2.93	-4.79
20	3.77	-4.07
30	4.35	-3.36
40	4.83	-2.52
50	5.51	-1.72
60	6.12	-1.33
70	5.92	-1.42
80	5.11	-1.81
90	4.36	-2.27
100	3.83	-2.9
110	3.47	-3.66
120	2.81	-4.4

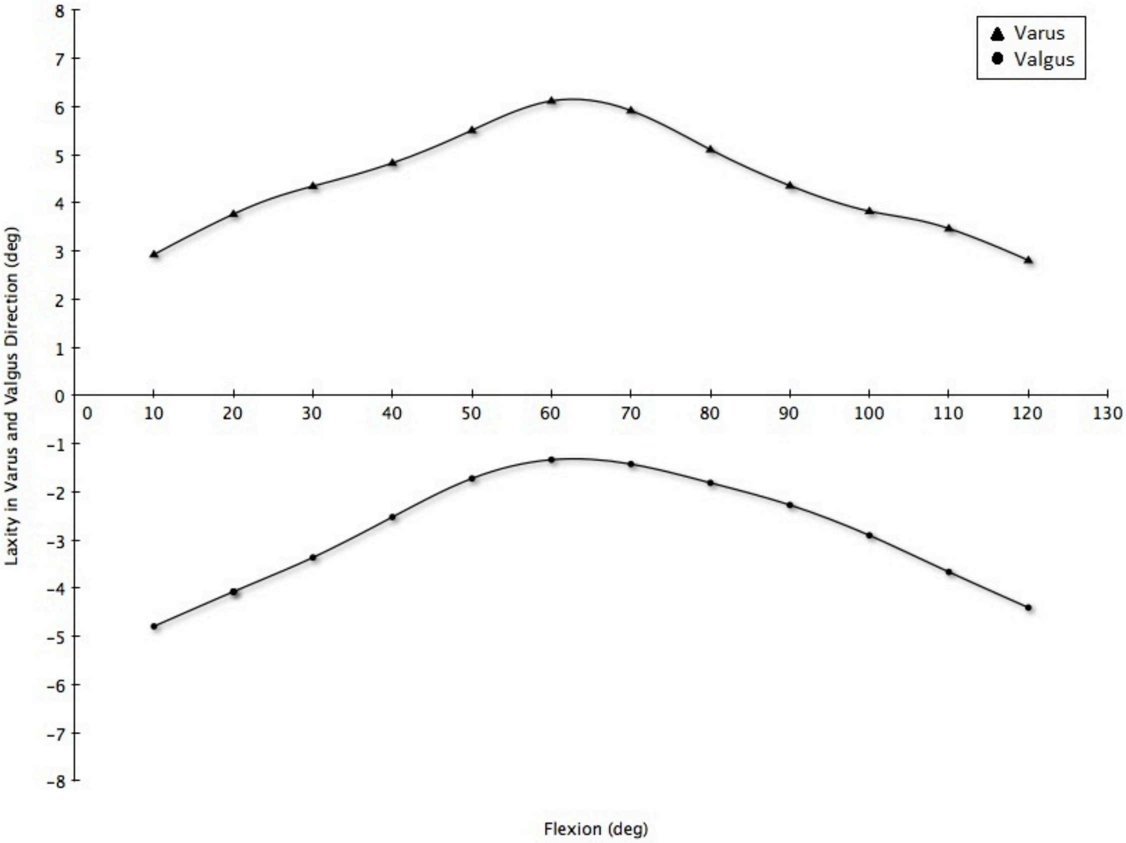

Figure 4.2: 15N Loaded Anatomic Elbow Joint and Varus-Valgus Laxity

4.1.2.2 Laxity Measurement with a 50N Load

Varus-Valgus laxity is measured for the anatomic elbow joint with a 50N applied load and results are shown in Table 4.3 and illustrated in Figure 4.3.

Table 4.3: 50N Loaded Anatomic Elbow Joint and Varus-Valgus Laxity

Flexion (Deg)	Varus (Deg)	Valgus (Deg)
10	5.65	-9.73
20	7.52	-8.13
30	8.63	-7.09
40	9.71	-6.02
50	10.82	-5.28
60	11.62	-4.58
70	11.43	-4.16
80	10.51	-5.04
90	9.68	-6.23
100	8.78	-7.47
110	7.46	-8.86
120	5.31	-10.11

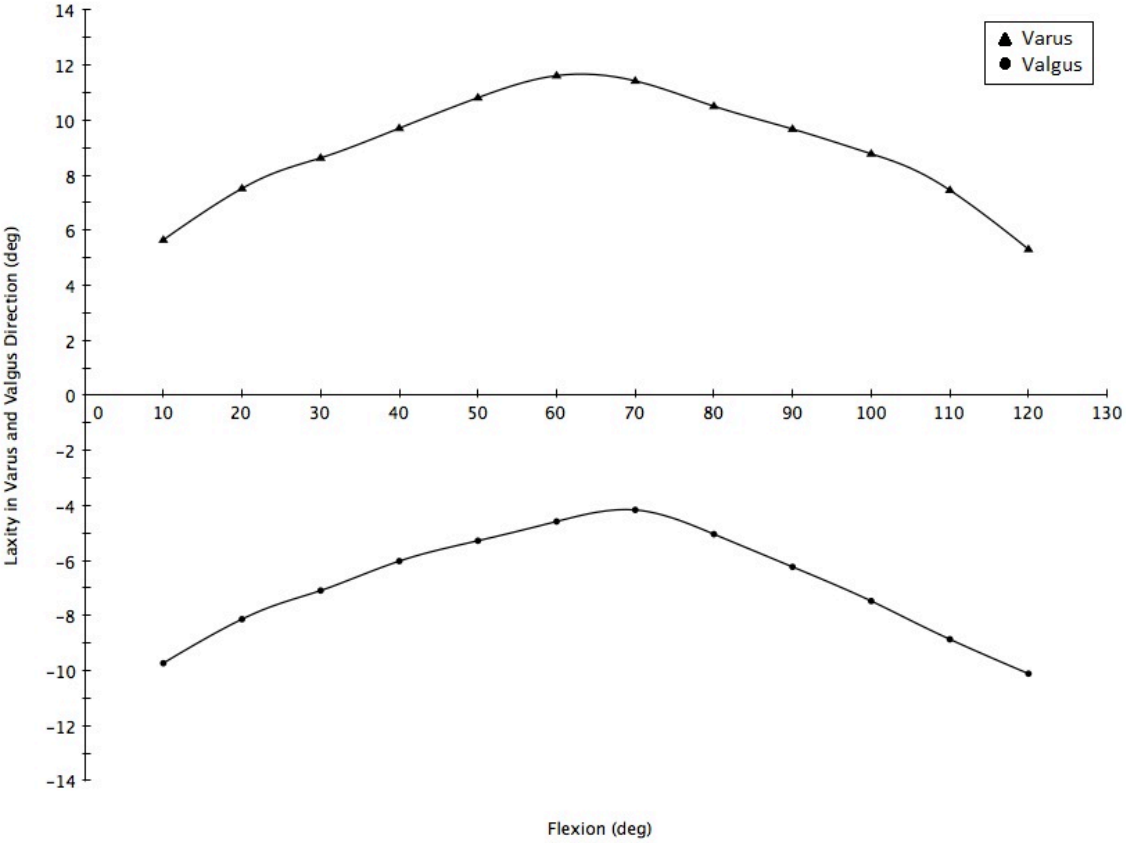

Figure 4.3: 50N Loaded Anatomic Elbow Joint and Varus-Valgus Laxity

4.2 FE Analysis of Artificial Elbow Joint

4.2.1 Von Mises Stress

Stresses on the ulnar part of the implant during flexion motion at t=2s are shown in Figure 4.4.

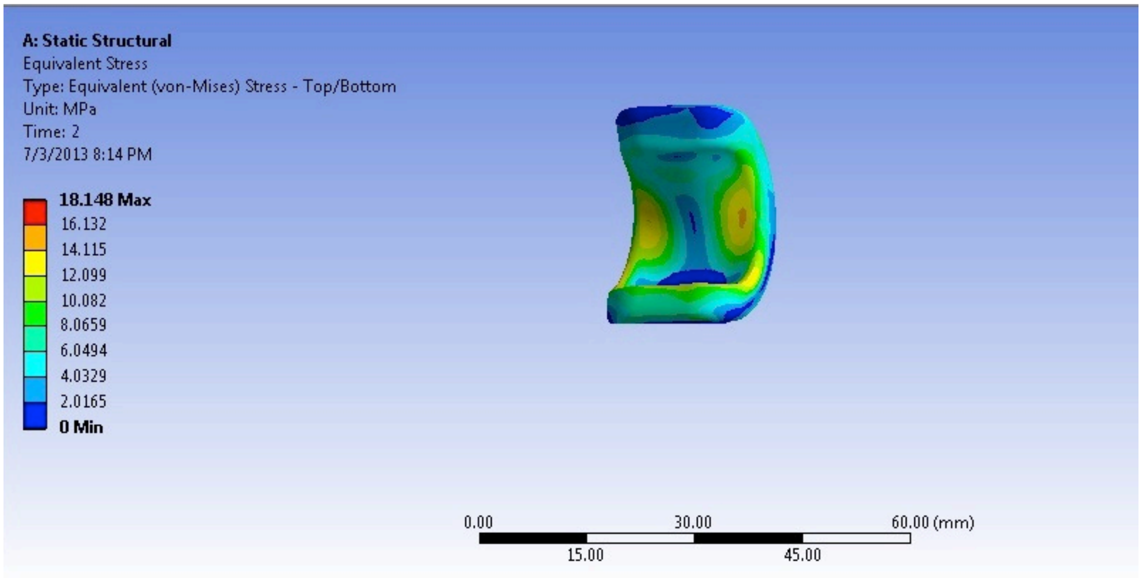

Figure 4.4: Von Mises Stress Distribution on the Ulnar Part of the Implant at t=2s

The results of Von Mises stress analysis are obtained and the maximum stresses on the ulnar part of the implant are given in Table 4.4 and demonstrated in Figure 4.5.

Table 4.4: Maximum Von Mises Stress on the Ulnar Part of the Implant

Time (s)	Max Stress (MPa)
0.4	15.672
0.8	15.083
1.2	16.247
1.6	16.261
2	16.893
2.4	16.648
2.8	17.314
3.2	17.662
3.6	17.526
4	18.148

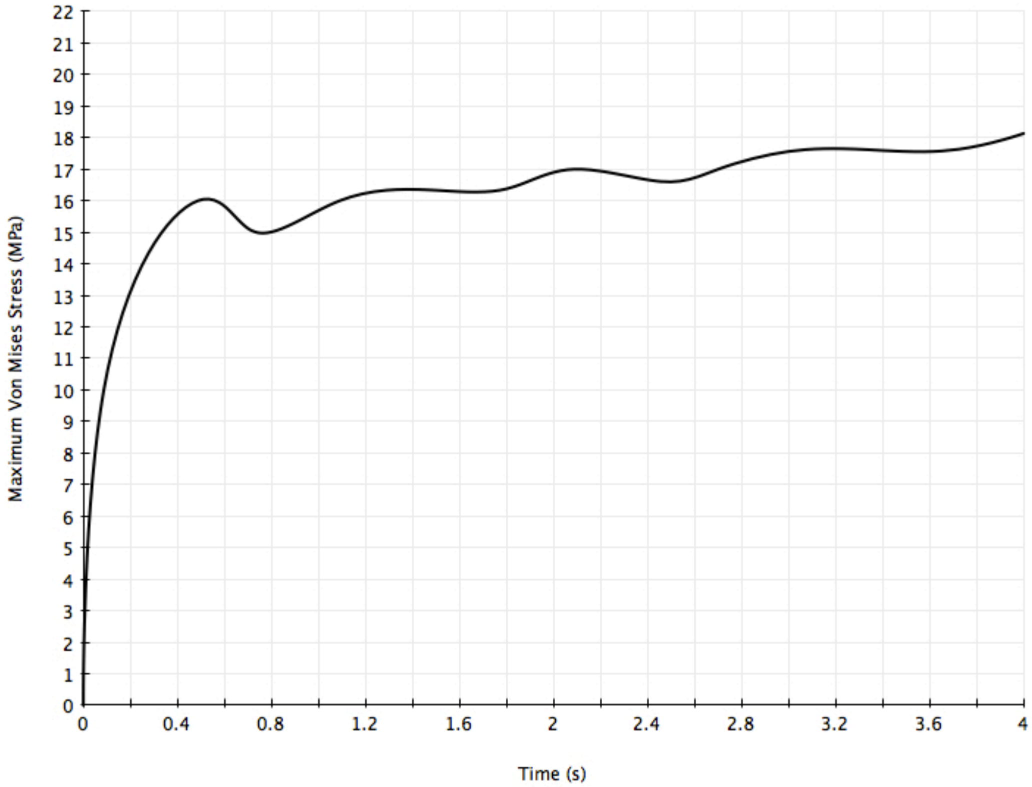

Figure 4.5: Maximum Von Mises Stress on the Ulnar Part of the Implant

4.2.2 Varus-Valgus Laxity Measurement

4.2.2.1 Laxity Measurement with 15N Load

Results of the measurement of Varus-Valgus laxity in artificial elbow joint with a load approximately equal to the gravity load (15N) are given in Table 4.5 and graphed in Figure 4.6.

Table 4.5: 15N Loaded Artificial Elbow Joint and Varus-Valgus Laxity

Flexion (Deg)	Varus (Deg)	Valgus (Deg)
10	10.39	-15.81
20	11.63	-14.06
30	12.7	-12.16
40	13.64	-10.29
50	14.12	-8.1
60	14.57	-6.78
70	15.13	-7.33
80	13.93	-8.24
90	12.85	-9.92
100	11.72	-11.56
110	10.66	-12.85
120	9.71	-14.25

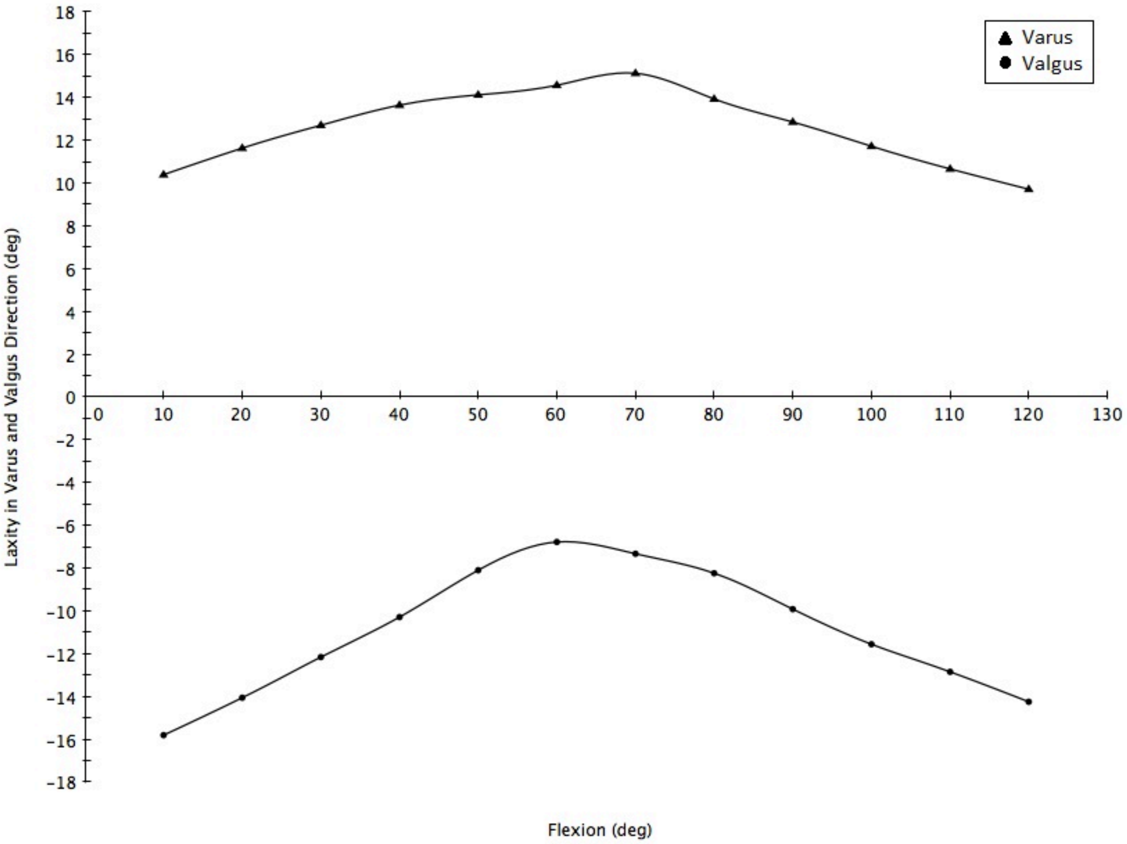

Figure 4.6: 15N Loaded Artificial Elbow Joint and Varus-Valgus Laxity

4.2.2.2 Laxity Measurement with a 50N Load

Varus-Valgus laxity assessment is performed for the artificial elbow joint and the outcomes are shown in Table 4.6 and demonstrated in Figure 4.7.

Table 4.6: 50N Loaded Artificial Elbow Joint and Varus-Valgus Laxity

Flexion (Deg)	Varus (Deg)	Valgus (Deg)
10	28.3	-31.6
20	33.4	-28.9
30	37.1	-26.7
40	39.9	-24.7
50	42.7	-22.2
60	44.3	-20.3
70	41.8	-21.6
80	38.3	-22.7
90	36.1	-24
100	33.2	-25.6
110	29.8	-27.5
120	26.7	-29.9

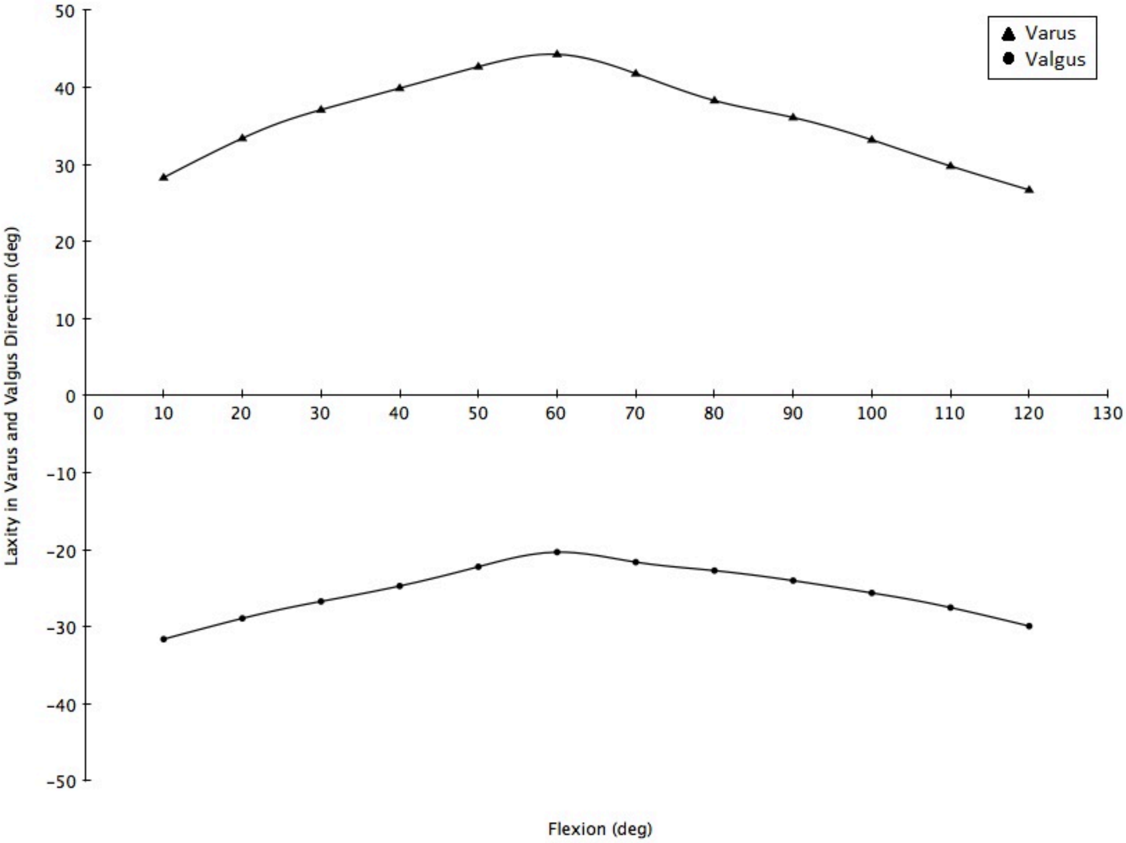

Figure 4.7: 50N Loaded Artificial Elbow Joint and Varus-Valgus Laxity

Chapter 5

DISCUSSION

In this chapter the obtained results from previous steps are discussed. The outcomes of this study indicate the differences between an anatomic elbow joint and an implanted elbow joint. Furthermore limitations of an artificial elbow joint in comparison with an anatomic elbow joint are represented.

5.1 Von Mises Equivalent Stress Distribution

This part of analysis includes some limitations in order to decrease the time of the process. For instance, the surfaces of the bones are simplified, sharp edges are omitted, the contacts interactions are assumed as frictionless and tissues are neglected.

In this study Von Mises stresses are evaluated because the results of Von Mises stress assessment are more reliable than normal stress evaluation. The normal stresses in X, Y and Z directions may not cause failure separately but the combination of the stresses in these directions may lead the failure of an object.

Maximum Von Mises stresses are obtained for anatomic and artificial elbow joint and approximately 20% increase of stress is observed in the results on the ulnar part of implanted elbow in comparison with normal elbow. According to the Von Mises stress distribution maximum stresses are observed in the two side of the ulnar part of the implant near the edges. The obtained maximum stress for the implanted elbow is under the yield strength point of the implant's material. However, the implant components will not be deformed and failed under the achieved maximum stress, nevertheless wear and corrosion will be occurred in polyethylene part of the implant over time and eventually it leads to failure of the implant.

5.2 Varus-Valgus Laxity

In the literature the maximum degree of varus-valgus laxity for normal anatomic elbow joint is approximately +5 for varus and -5 for valgus. In this study the results of the simulated model with an applied equivalent gravity-load to forearm are close to the literature for the anatomic elbow joint, where the maximum degree of varus-valgus laxity for normal anatomic elbow joint is almost +6 for varus and -5 for valgus.

Analyses are performed in four different conditions, i.e., two analyses for anatomic elbow joint with a normal and a 50N load respectively and the same analyses for the artificial elbow joint as well. The maximum degree of laxity for the varus is between 60-70° and the minimum degree of the varus is in the 10° and 120° of flexion. On the other hand, the maximum degree of valgus laxity is in the 10° and 120° and the minimum degree of laxity is between 60-70° of flexion. These procedures are observed in the analyses for both the gravity-loaded and a 50N load FE models of anatomic and artificial elbow joint.

The obtained results show that the implanted elbow has larger degrees of varus-valgus laxity in comparison with anatomic elbow joint. With the implanted elbow joint, the degree of laxity is shown to be significantly larger by increasing load. Results indicate that implanted elbow joint brings much larger degrees of varus-valgus laxity to the joint, which is a result of implant failure, and future elbow implants need better designs to be more efficient.

Chapter 6

CONCLUSION AND FUTURE WORKS

In this study SolidWorks® program were used to create 3D models of elbow joint implants and the models were evaluated by using ANSYS software, where the Von Mises stress and varus-valgus laxity were analyzed for anatomic elbow joint and artificial elbow joint. Then the obtained results from the analyses for anatomic and artificial elbow joints are compared. The results of varus-valgus laxity and Von Mises stress evaluations showed remarkable changes between normal and implanted elbow joint. Some limitations applied in the analyses in order to decreasing the time of the process due to the lack of a high performance computer. On the other hand, the obtained results indicate that the implanted elbow has some limitations and problems in term of movements in comparison with normal elbow. Furthermore implanted elbow is under more pressure and stresses than normal elbow, which is a result of wear, corrosion and finally failure of the implants over time. An increase of approximately 20% of maximum Von Mises stresses is observed in the results of implanted elbow joint in comparison with normal elbow, which is due to the stress concentration on ulnar part of the implant.

It is advised that a complete FE model of elbow joint may be created and may be analyzed in order to increase the accuracy of the results. The new FE model may consist of all the tendons, ligaments, muscles and etc., moreover, friction can take a part in the analyses. Implant and bony parts of the FE model need to be more accurate and in a high quality to make the meshing and analyses better.

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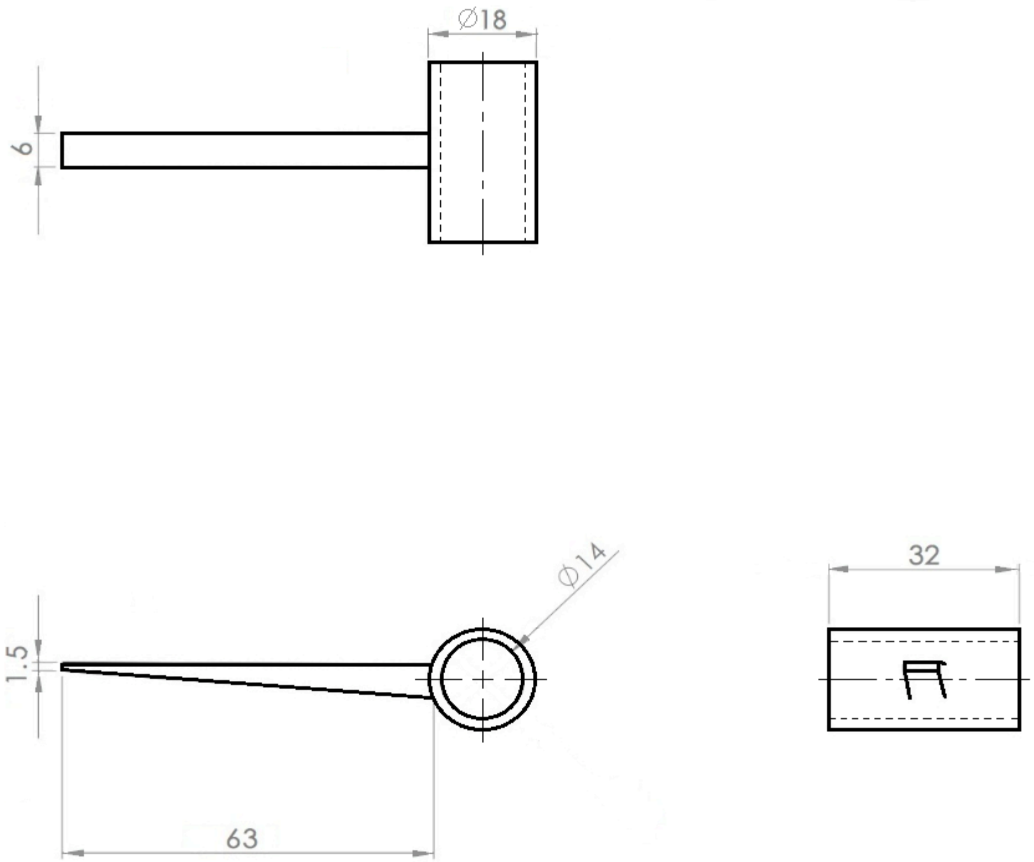
APPENDICES

Appendix 1



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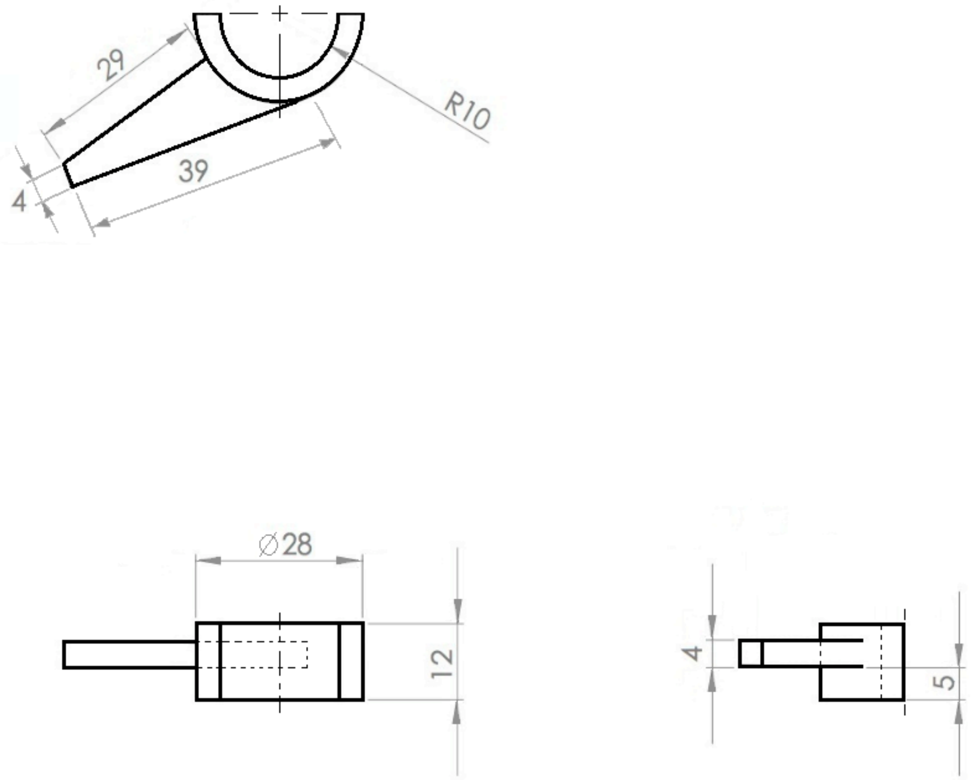
Appendix 2



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