Chapter 1

General Introduction

1.1 Introduction

During the last two decades, research on Total Shoulder Replacement may be considered as scarce, as compared to the comprehensive literature on Total Hip and Knee Replacements. The reason behind this scarcity may be attributed to the high demand for Total Hip Arthroplasty (THA) and Total Knee Arthroplasty (TKA) in recent times, as compared to the Total Shoulder Arthroplasty (TSA). According to the American Academy of Orthopaedic Surgeons, during 1990 – 1995, a total number of 1,060,000 TKA and 746,000 THA was performed compared to only 26,000 TSA (Source: National Centre for Health Statistics, 1990-1995; data extracted and analysed by American Academy of Orthopaedic Surgeons, Department of Research and Scientific Affairs). However, with the increasing number of shoulder complications in normal as well as prosthetic joints and the demand for improved shoulder prostheses, in particular the glenoid prostheses, research on TSA is increasing rapidly. As compared to other commonly performed arthroplasties, like the hip and the knee, the TSA involves a far more complicated procedure with a greater potential for errors and complications in fulfilling the objective to restore the large range of motions.

Research in the shoulder region is mainly focused on the glenohumeral joint. The terms shoulder and shoulder joint are commonly used to denote the glenohumeral joint. The shoulder is a multifunctional joint with an infinite number of functions ranging from manipulating objects, throwing a ball and rising from a chair to lifting a heavy load. The shoulder girdle (Fig. 1) consists of the clavicle (collarbone) and the scapula (shoulder blade). The scapula is not only connected to the thorax (rib cage) via the clavicle, but also slides at the backside over the thorax. Motions of the shoulder girdle are closely related to the motions of the humerus. The combined motion of the scapula and the humerus is referred to as the scapulohumeral rhythm. The normal motions of the shoulder are: abduction and adduction, flexion and extension, horizontal flexion and extension, exorotation and endorotation.

1.2 The shoulder mechanism

The shoulder mechanism is an example of a very complex musculoskeletal structure consisting of a chain of bones connecting the upper extremity to the trunk. The shoulder girdle consists of a scapula and a clavicle and functions as a movable but stable base for the motions of the humerus (Fig. 1). The shoulder comprises of three synovial joints which interconnect the bones:

- The sternoclavicular (SC-) joint, connecting the sternum part of the thorax to the clavicle.
- The acromioclavicular (AC-) joint, connecting the clavicle to the acromion of the scapula.
- The glenohumeral (GH-) joint, usually represented by a ball-and-socket joint between the glenoid cavity of the scapula and the head of the humerus (Fig. 2).

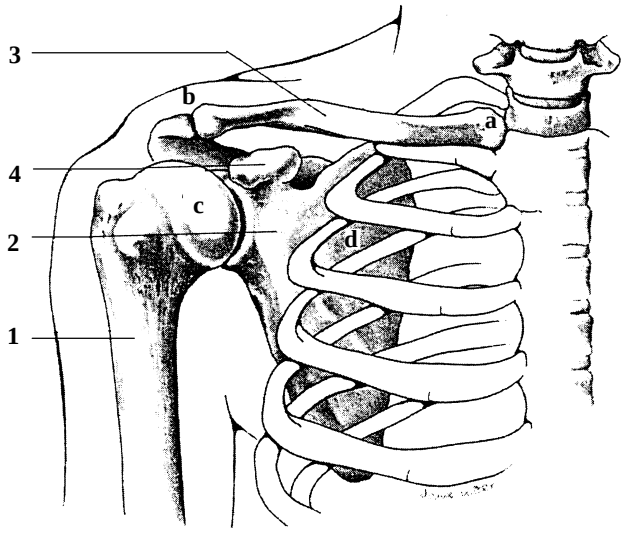


Figure 1. The bony structure and joints of the shoulder girdle (Stenvers, 1994). 1. Humerus; 2. Scapula; 3. Clavicle; 4. Coracoid Process; a. SternoClavicular (SC) joint; b. AcromioClavicular (AC) joint; c. GlenoHumeral (GH) joint; d. ScapuloThoracic Gliding Plane (STGP).

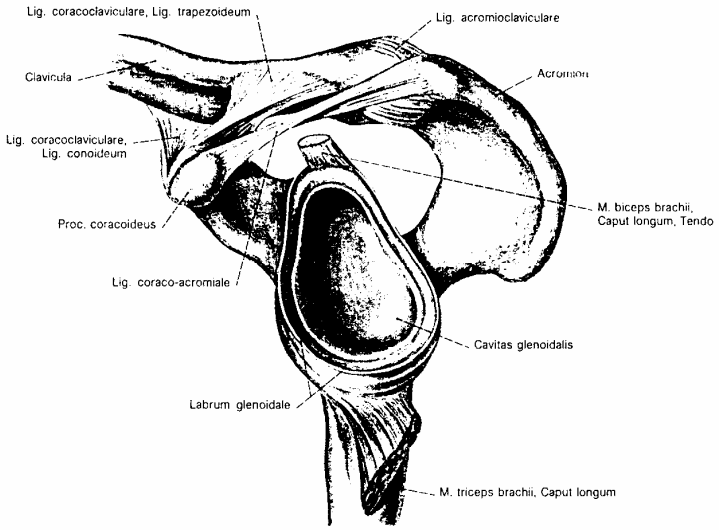


Figure 2. A view of the glenoid cavity, in which the humeral head articulates, with the surrounding anatomical structure (adapted from Sobotta, 1988).

Table 1. The seventeen muscles of the shoulder mechanism with subdivision of the muscles in 20 functional parts and ninety-five muscle lines of action (Van der Helm, 1991). The abbreviation m. stands for muscles (Fig. 3).

Muscle	Part	Origin	Insertion	Number of muscle lines of action
m. trapezius	pars clavicularis	thorax	clavicle	6
	pars scapularis	thorax	scapula	6
m. levator scapulae		thorax	scapula	3
m. rhomboideus		thorax	scapula	3
m. pectoralis minor		thorax	scapula	4
m. subclavius		thorax	clavicle	-
m. serratus anterior		thorax	scapula	6
m. latissimus dorsi		thorax	humerus	5
m. pectoralis major	pars clavicularis	clavicle	humerus	5
	pars thoracalis	thorax	humerus	5
m. deltoideus	pars clavicularis	clavicle	humerus	6
	pars scapularis	scapula	humerus	6
m. coracobrachialis		scapula	humerus	6
m. teres major		scapula	humerus	6
m. teres minor		scapula	humerus	6
m. infraspinatus		scapula	humerus	6
m. supraspinatus		scapula	humerus	6
m. subscapularis		scapula	humerus	6
m. triceps	caput longum	scapula	ulna	2
m. biceps	caput longum	scapula	radius	1
	caput breve	scapula	radius	1

The articulating geometry of these synovial joints is complex. For many purposes they can be regarded as ball joints, neglecting the possibility of small translations. During movement of the arm, the medial border of the scapula slides over the dorsal side of the thoracic cage, pressed onto it by the combined action of muscles. This connection gives rise to a fourth joint, the Scapulo-Thoracic Gliding Plane (STGP). The double connection between the scapula and the thorax, one via the clavicle and the other by the STGP makes the system a closed chain mechanism. There are three extracapsular ligaments in the shoulder girdle: the costoclavicular ligament limiting the range of motion of the SC-joint and the conoid and trapezoid ligament acting at the AC-joint. Seventeen muscles are crossing the joints of the shoulder mechanism; most of them are polyarticular, fan-shaped and have large attachment sites. The locations of the muscles are shown in two views in Figures 3a and 3b. The muscles were divided into twenty different muscle parts based on the joints that each muscle part crossed. Based on the muscle fibre distribution within a muscle, each of these muscles was represented by 1 to 6 muscle lines of action of force between origin and insertion (Van der Helm and Veenbaas, 1991). A classification of the muscles and muscle parts for the shoulder mechanism is presented in Table 1.

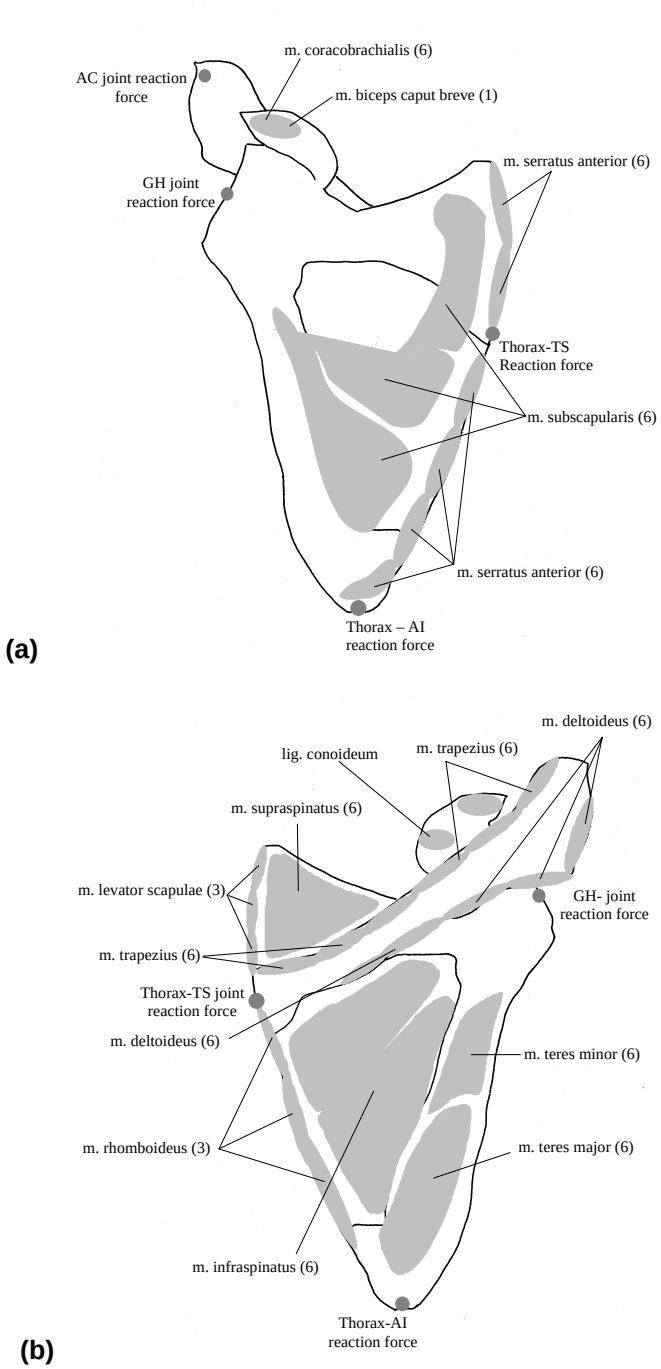


Figure 3. The locations of the muscles (m.) and the joint reaction forces in the scapula. Numbers within bracket indicate the number of muscle lines of action. (a) ventral view; (b) dorsal view.

In contrast to the pelvic girdle, a considerable range of motion is achieved by the shoulder girdle. Although the motions of the scapula are severely constrained, the large range of motion of the humerus is due to the simultaneous motions at the SC-, AC- and GH- joints.

1.2.1 The scapula

The scapula is a large, flat, triangular bone consisting of five solid bony ridges (glenoid, scapular spine, lateral border, medial border and coracoid process) and two thin, hard laminated structures (infraspinous and supraspinous fossa). The infraspinous fossa is surrounded by the glenoid, the scapular spine, the medial border, and the lateral border. The structure of the scapula, in two views (ventral and dorsal) is shown in Figures 4a and 4b. It is subject to a number of muscle forces, ligament and joint reaction forces during motions of the arm. The quantitative and qualitative estimates of all the muscle, ligament and joint reaction forces acting on the scapula, during activities like unloaded humeral abduction, unloaded anteflexion, loaded abduction and loaded anteflexion was investigated extensively by Van der Helm (1994[a,b]). It seems, from the location, magnitude and direction of these forces that the scapula is loaded all over its structure. The primary function of the scapula is two-fold. On the one hand it offers an additional joint, so that the total rotation of the humerus with respect to the thorax can increase. On the other, it is a large bone, where the muscles have large lever arms with respect to the SC- and AC- joint. Hence, smaller muscles are sufficient to provide the necessary moments, which are in general larger than the moments around the GH- joint. The shape of the scapula provides large moment about SC- and AC-joint. This function is more important for the particular shape of the scapula.

1.3 Gleno-humeral arthroplasty: state-of-the-art

In 1893, Jules Emile Pean (1830 – 1898), a French surgeon, performed the shoulder replacement in a patient with arthritis of the shoulder for the first time (Lungi, 1978). He used a prosthesis made of platinum and rubber, which lasted for approximately two years after implantation and was removed because of uncontrollable inflammation. Despite this complication, the short-term benefits were encouraging and the advent of shoulder arthroplasty was realised.

Shoulder arthroplasty can be classified into two types: the hemi-arthroplasty and the total shoulder arthroplasty. In the former, a humeral component is inserted into the humerus while the scapula remains intact causing a direct metal-bone contact. In the TSA, in addition to the humeral component, a glenoid component is inserted into the glenoid part of the scapula. Hemi-arthroplasty of the shoulder has given excellent results for glenohumeral arthritis in patients with massive irreparable rotator cuff tears (Wirth and Rockwood, 1996). It has the advantage of avoiding a relatively complicated procedure of the insertion of glenoid prosthesis, which requires high technical skill of the surgeon. However, because of the imperfect fit of humeral head in the glenoid cavity, TSA is more widely used.

The TSA involves the reconstruction of GH-joint (Fig. 2), when it is affected by osteoarthritis, rheumatoid arthritis and fractures or dislocations with traumatic arthritis. It was born with the introduction of new total polyethylene glenoid component by Neer (1974). The Neer I prosthesis has been used extensively for the past twenty years and is still widely used. In 1984, Neer introduced the metal-backed polyethylene component as the Neer II prosthesis.

Aseptic glenoid loosening is the most-frequently-encountered complication threatening the TSA (Cofield, 1984; Barrett et al., 1989; Berms, 1993; Sneppen et al., 1996; Torchia et al., 1997;

Sperling et al., 1998; Wallace et al., 1999). Loosening is defined as the progression of radiolucent lines exceeding 1.5 mm in width or any definite change in the position of the component (Stewart and Kelly, 1997; Torchia et al., 1997; Wallace et al., 1999). It is hastened by conforming prostheses, incorrect positioning, rotator cuff tears, and capsular contractures, but it can be protected by secure glenoid fixation. Loosening may occur shortly after surgery, probably due to excessive stresses in the cement, or at the interfaces of cement-bone, implant-cement and implant-bone. Medium (3 to 10 years) and long term (10 years or more) follow-up observations show radiographic changes that indicated loosening (McCullagh, 1995; Berms, 1993; Sneppen et al., 1996; Torchia et al., 1997; Sperling et al., 1998; Skirving, 1999; Wallace et al., 1999). This may be due to bone remodelling, which is caused by TSA induced changes in the stress distributions.

Although cement has been most widely used to achieve almost immediate fixation of the implant with bone, it has been susceptible to failure within itself and at the interfaces with other materials. The uncemented glenoid prosthesis with bone-ingrowth surface emerged as an alternative possibility to the cemented designs. However, variations in the design of uncemented glenoid component were few and the use was limited to patients having a relatively good quality bone stock. Clinical and radiographic feedbacks on uncemented glenoid prosthesis were encouraging as compared to the cemented prostheses (Cofield, 1994; Wallace et al., 1999). The major variable of the study, by Wallace et al., 1999, was the method of fixation of the glenoid component. The results of this study revealed that fixation without cement provided an outcome that was comparable to that fixed with cement, in terms of relief of pain, subjective functional capacity, range of motion, and effect on general health. These findings were consistent with other studies on TSA performed with cement (Barrett et al., 1987; Cofield, 1984; Hawkins et al., 1989; Matsen et al., 1996) or without cement (Franklin et al., 1988; Cofield and Daly, 1992). The overall rate of complications was also similar to those in previous reports (Cofield and Edgerton, 1990; Cofield, 1994; Wirth and Rockwood, 1996). However, the overall prevalence of radiolucent lines associated with the cemented implants was higher than that in case of the uncemented implants (Wallace et al., 1999).

TSA is a technically difficult procedure, with perhaps a greater potential for errors and complications as compared to other commonly performed arthroplasties, like the hip and the knee. In general, the restoration of functional capabilities and the patient satisfaction are considered to be far from normal. For example, a long-term study by Sperling et al. (1998) reported that the results of TSA were considered to be satisfactory if the patient had no or slight pain or moderate pain only with vigorous activity, had external rotation of at least 20 degrees, had active abduction of at least 90 degrees, and was satisfied with the procedure. The likelihood of mechanical failure depends on the stresses induced within the implant material and at the material interfaces as compared to the strength of the material and the interfaces (Huiskes, 1993[a]). Together with the higher stresses evoked in the polyethylene cup, the risk of wear and wear debris formation in these areas might be accelerated in a few cases (Wirth and Rockwood, 1994). From anatomic point of view, a small volume of bone, available for fixation of the glenoid component, is a major limitation in the TSA (Cofield, 1984). CT-scans of the glenoid of a normal healthy person reveal that the cancellous bone has a higher density anteriorly and posteriorly than centrally (Anglin et al., 1999; Müller-Gerbl et al., 1992).

In the biomechanical study on stability and fixation of glenoid components, Fukuda et al. (1988) remarked that the fixation strength of glenoid component was lowest for the Neer I prosthesis (total polyethylene design). The study focuses on comparisons between the types of glenoid prostheses – the metal-backed polyethylene and the non-backed polyethylene.

Table 2. Investigation with cemented glenoid prosthesis (without revision surgery).
PE - PolyEthylene; MB – Metal-Backed polyethylene; N.R. – data Not Recorded.

Author, year	Design	Follow-up period (years)	No. of shoulders	Percentage of defective glenoid component	
				Radio-lucency	*Loosen-ing*
Amstutz et al., 1981	DANA	2 – 10	56	94	4
Neer et al., 1982	Neer I (PE, MB)	2 – 8.25	194	30	0
Cofield, 1984	Neer I	2 – 6.5	73	82	21
Barrett et al., 1987	Neer I	2 – 7.5	50	74	18
Barrett et al., 1989	Neer I (PE) & Neer II (MB)	2 – 11	129	82	10
Hawkins et al., 1989	Neer I	2 – 8.6	70	Nearly all	7
Boyd et al., 1990	Neer I	2 – 10.3	131	N.R.	12
Sneppen et al., 1996	Neer II	4.3 – 11.6	62	21	40
Torchia et al., 1997	Neer I	5 – 17	89	84	82
Stewart and Kelly, 1997	Neer II	7 – 13	37	62	24
Sperling et al., 1998	Neer I	5 – 20	32	59	28
Wallace et al., 1999	Neer II (PE and MB), Cofield (PE), Global (PE)	3.8 – 7.5	32	41	25

In general, all metal backed glenoid components appeared to have sufficient fixation strength against normal shoulder joint forces. The strength of highly porous spongy bone is low, which adds to the complications of fixation of the prosthesis in the glenoid (Frich et al., 1997). Hence, it becomes a real challenge to design a glenoid prosthesis that can maintain secure fixation during the normal movements of the arm.

1.4 The cemented and the uncemented glenoid prostheses

Since the introduction of Neer I prosthesis in the 1970s, several designs closely resembling the Neer I and II prostheses, were developed (Amstutz et al., 1981; Amstutz et al., 1988; Cofield, 1984). The glenoid prosthesis consists of a polyethylene cup with a keel to anchor inside the scapula.

Table 3. Investigation with uncemented glenoid prosthesis (upgraded from Cofield, 1994).

Author, year	Design	Fixation	No. of shoulders	Number of defective glenoid component	
				Radio-lucency	*Loosen-ing*
Bayley and Kessel, 1982	Kessel	Pressfit	33	0	0
McElwain and English, 1987	English-Macnab	Tissue-ingrowth	13	1	1
Copeland, 1990		Pressfit	20	0	0
Roper et al., 1990	Roper-Day	Pressfit	13	1	1
Weiss et al., 1990	English-Macnab	Tissue-ingrowth	9	1	0
Brostrom et al., 1992	Kessel	Pressfit	23	13	2
Cofield and Daly, 1992	Cofield	Tissue-ingrowth	31	3	1
Cofield, 1994	Cofield	Tissue-ingrowth	180	6	4
Wallace et al., 1999	Cofield	Tissue-ingrowth	26	6	2

The designs of these components differ mainly in the radius of the curvature of the cup and the shape of the keel. A larger radius of curvature of the glenoid as compared to the humeral head would allow translation during movement. However, it would lead to an increase in the contact stresses, resulting due to nonconformity of the surfaces in contact. Metal-backed polyethylene component and the use of bone-ingrowth surface (only for metal-backed) are also available.

Clinical and radiographic investigations, mostly with the Neer I (total polyethylene glenoid), and the Neer II (all-polyethylene and metal backed polyethylene glenoid) prostheses, have revealed potential complications with possible revisions and recommendations. Post-operative complications are important in the light of the increasing number of patients who receive shoulder replacements. Component loosening has been identified as the most frequently (33%) occurring complication apart from instability of the rotator cuff, rotator cuff tear, periprosthetic fracture, nerve injury, infection, size of implant and dysfunction of the deltoid muscle (Wirth and Rockwood, 1996). A summary of the radiographic and clinical studies on the cemented glenoid prosthesis is presented in Table 2.

The use of polymethylmethacrylate (PMMA) for fixation of the glenoid prosthesis has been one of the most-frequently-occurring problems in TSA. It has been widely used and preferred, because the fixation of the implant in the bone can be achieved almost immediately. But the use of PMMA has been reported to be less reliable, particularly in the presence of instability or massive tear of the rotator cuff (Barrett et al., 1987; Franklin et al., 1988; Weiss et al., 1990). In some reports, both the total-polyethylene and the metal-backed components fixed with cement

demonstrated radiographic lucent lines at the cement-bone interface of the glenoid component (Amstutz et al., 1988; Cofield and Daly, 1992). Even with modern cementing techniques the progression of radiolucent lines was observed in at least 20 percent of the cases and it was associated with pain and decreased functional capabilities (Cofield, 1983; Cofield, 1984; Norris and Lachiewicz, 1996).

The problem of progressive radiographic changes, the long term efficacy of the cement, and the need for revision of cemented glenoid components have prompted the development of implants with porous surfaces having capabilities of bone-ingrowth to achieve secure fixation with bone. Insertion without cement, of a glenoid component with tissue-ingrowth capability, is not a new concept. But the technique is yet to gain wide acceptance. Cofield (1994) and Wallace et al. (1999) retrospectively reviewed clinically evident loosening of glenoid components, inserted with and without cement. Both these studies remarked that despite the number of complications, the results of uncemented glenoid component were very similar to those reported for TSA using the cemented glenoid component. One of the several features observed in the merit analysis of TSA, was the striking lack of radiographic changes at the implant-bone interface. As compared to the cemented version, slightly increased frequency of high-density polyethylene wears and displacement of the polyethylene from the metal tray, were observed for the uncemented design. A summary of the radiographic and clinical investigation with uncemented glenoid prosthesis is presented in Table 3.

Design variations in the uncemented glenoid prosthesis are few. Most of them consist of, in principle, a polyethylene cup with a metal-backing with tissue-ingrowth capability. Interestingly, one of the earliest forms of TSA possessed tissue-ingrowth at the glenoid and the humeral components (McElwain and English, 1987). The Kessel prosthesis with press fit design, the Cofield metal-backed design with tissue-ingrowth capability, and the Bio-modular porous coated glenoid components (Biomet Inc., Warsaw, Indiana) were developed and continued to be used. Only selected patients, having good bone stock were recommended for the use of these porous coated uncemented prostheses. Some biomechanical studies on uncemented glenoid prostheses, however, were inadequate to draw significant conclusions on the design of the implant (Orr et al., 1988; Stone et al., 1999).

1.4.1 Failure scenarios

The failure scenarios for total hip arthoplasty, introduced by Huiskes (1993[a]) are also useful, more or less, to analyse failure mechanisms of other reconstructed joints like the TSA. Although the failure of an implant is mainly due to biological causes, the initiation of the failure process may be due to mechanical events. Two dominant failure scenarios of the cemented reconstruction can be identified (Huiskes, 1993[a]).

(1) According to the *accumulated-damage failure scenario*, the materials or interfaces are too weak to sustain the effect of long-term, dynamic loads applied on the implants. The likelihood of mechanical failure depends on the stress induced in a material versus the strength of that material. The repetitive nature of the external loads generates high dynamic stresses in the materials and at the interfaces. As a result, mechanical damage, typically micro-cracks, is gradually accumulated in the cement. These micro-cracks reduce the strength of the cement and its bonds at the layer of interface between implant and bone, eventually causing failure. In case of uncemented prostheses, loosening may occur due to the failure of the implant-bone interface as well as the polyethylene-metal interface. The polyethylene cup may be dissociated from the metal-backing, which may still maintain a secure fixation with bone, thus resulting in failure of the prosthesis. The eventual gross

loosening of the implant may be due to the cement-bone interface loosening, failure (cracking) of the cement due to excessive stresses, and relative motions between the materials.

(2) According to the *particulate-reaction failure scenarios*, the cement-bone interface gradually disintegrates due to the migration of wear particles. These tiny particles may be polyethylene debris, abraded from the cup of glenoid prosthesis, cement particles abraded from the cement mantle, or metal debris burnished from the implant. The polyethylene wear debris, in particular, is considered to be a major threat to any arthroplasty. These wear debris cause particulate reactions by macrophages, osteolysis, soft tissue interposition and finally gross loosening.

In this study, particle generation was not really used. Only, mechanical damage due to stresses has been studied. However, the effect due to progressive damage accumulation in different material has not been studied. The initial stress distribution in the implant-bone structure has been critically examined with regard to the strength of the material. The multi-axial stresses at the interface of the different material have been evaluated. The comparisons and evaluations of the study were based on (1) fixation technique – cemented and uncemented, (2) type of the implant – metal-backed or non-backed. The study is considered to be a first major step towards understanding the load transfer mechanism in the glenoid prostheses and to identify the mechanical factors responsible for the loosening of the implant, postoperatively.

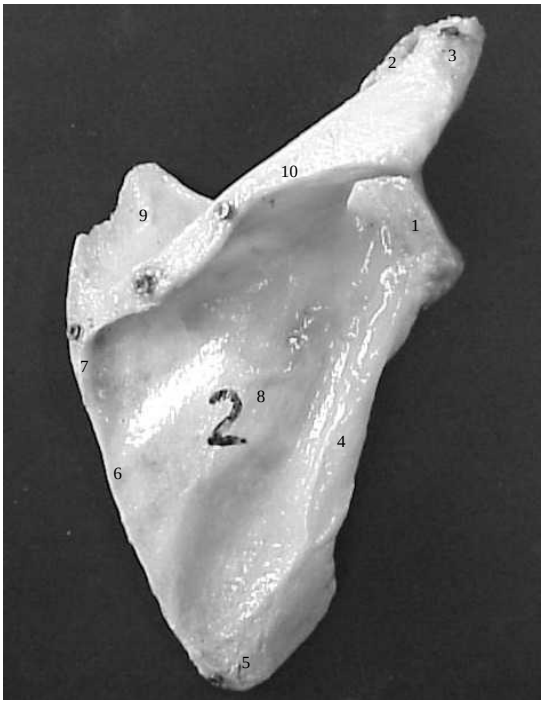
1.5 Finite element model of the scapula

Stress analysis is required for evaluations on implant-bone configuration. It helps in design, failure prediction and improvement of an implant. The introduction of computer modelling techniques, in particular, the finite element method, offers the possibility to test and to validate certain clinical hypotheses rigorously (Huiskes et al., 1987; Huiskes et al., 1989; Huiskes et al., 1992; Huiskes, 1993[a]; Huiskes, 1993[b]; Dalstra et al., 1995; Huiskes, 1997; Kerner et al., 1999). The basic tool used in this study is the Finite Element Method (FEM), which has emerged as an important tool in orthopaedic research to determine stresses and strains in bone and in various components concerning the fixation of artificial joints and the effect of adaptive bone remodelling. It is a fast and efficient pre-clinical testing method to visualise biomechanical problems as compared to the clinical follow-up procedure.

Studies related to FE analysis of the scapula were mostly restricted to two-dimensional (2-D) models of the glenoid with or without a prosthesis (Orr et al., 1988; Friedman et al., 1992; Lacroix and Prendergast, 1997; Stone et al., 1999). The geometry, material properties and loading conditions of these models appeared to be far from real. The 2-D models can indicate certain trends in the stress distributions, but for more detailed evaluations, 3-D models are indispensable.

The 3-D model of Lacroix et al. (1997) and Lacroix et al. (2000) using CT-scan data was an effort in that direction. The errors involved in the FE modelling, however, were not discussed in these studies, thus making it difficult to assess the accuracy of FE representation. A number of investigators have reported 3-D FE modelling of bone (Keyak et al., 1990; Harrigan and Harris, 1991; Weinans et al., 1991; Keyak and Skinner, 1992; Keyak et al., 1993; Dalstra et al., 1995) using CT-scan data for various biomechanical studies. Unfortunately, until now, there has been hardly any report on the load transfer mechanism across a normal scapula, using a realistic 3-D FE model.

(a)



(b)

Figure 4. The scapula. (a) ventral view; (b) dorsal view.
1. Glenoid; 2. Coracoid Process; 3. Acromion; 4. Lateral border; 5. Angulus Inferior; 6. Medial border; 7. Trigonum Spinae; 8. Infraspinous fossa; 9. Supraspinous fossa; 10. Scapular spine.

The quality of a FE model and the accuracy of the results depend on the model itself, as compared to the actual conditions (normal bone or a bone with implant). The accuracy is highly dependent on the correct estimation and distribution of the elastic moduli of elements, constituting the FE model of the scapula. The anisotropy of cancellous bone has considerable effect on the mechanical properties. The type and size of finite elements is an important factor in the correct representation of the structure of bone, with or without implants. The convergence test has often been used to estimate the quality of the FE model. But a thorough experimental validation, though a very difficult and tedious procedure, has always been considered as the best tool to judge the quality of the numerical predictions. The FE models of femur (Keyak et al., 1993) and pelvic bone (Dalstra et al., 1995) were experimentally validated using strain gage technique. Therefore, an experimental validation of the FE model of the scapula using strain gage measurements is considered to be a major investigation. A new experimental set-up was required to test a fresh specimen of cadaveric scapula with strain gages attached all over its surface.

1.6 Motivation of the study

Although the mechanisms of glenoid loosening are not clearly defined, they have been associated with anatomical and biomechanical factors. The precise relationship between the cause and the effect, regarding aseptic loosening of the glenoid prostheses and the extent to which the mechanical factors play a role in this process, however, are not clearly understood yet. In order to analyse these biomechanical factors a detailed 3-D FE model of the glenoid prosthesis is required. These 2-D FE models accounted for several design parameters such as implant material, implant shape, method of fixation by screws or pegs and the use of metal backing (Orr et al., 1988; Friedman et al., 1992; Lacroix and Prendergast, 1997; Stone et al., 1999). But they excluded the detailed 3-D geometry and material properties of the glenoid. The complex shape of the scapula and the varying forces acting on it certainly requires a new approach using a detailed 3-D FE model.

Clinical and radiographic follow-up studies, though a few, reported encouraging results on the prospects of uncemented glenoid prosthesis. But, in order to reveal the biomechanical factors involved in the design of uncemented prosthesis and to develop a better understanding of the load transfer with regard to the potential failure mechanisms, a detailed 3-D FE analysis of the uncemented glenoid prosthesis is necessary. The 2-D FE studies (Orr et al., 1988; Stone et al., 1999), on several designs of uncemented glenoid prosthesis were inadequate to evaluate the implant design.

A realistic three-dimensional (3-D) FE model, using on Computed Tomography (CT) scan data, can reveal the function of constituent parts of a bone and can be useful in understanding the load transfer mechanism due to muscles, ligaments and joint reaction forces. This FE model can be further used for developing a submodel with fine mesh size in the domain of inclusion of the prosthesis to calculate stresses and strains in the different components and at the respective interfaces. These results may be useful in analysing some failure criteria and in recommending measures for improvement of the prostheses design.

1.7 Goal of the study

The primary goal of the study is to develop a better glenoid prosthesis. Therefore, the present study is aimed at investigating the glenoid load transfer mechanism with regard to probable failure scenarios of glenoid prostheses. Analysis of the failure criteria may suggest measures for improved glenoid prostheses. In order to achieve the primary goal, 3-D FE models of two fundamental designs

of cemented glenoid prostheses, one total polyethylene and the other, metal backed polyethylene, are certainly required. The possibilities of the uncemented glenoid prosthesis as compared to the cemented designs are also investigated, using FE stress analysis.

Before analysing an artificial (prosthetic) joint, it is advised to analyse a healthy functioning joint and to understand the basic mechanics of load transfer on a scapula, due to the action of muscles, ligaments, and joint reaction forces. A realistic 3-D FE model of the whole scapula along with the loading conditions taken from the static shoulder model (Van der Helm, 1994[a,b]), are required for assessing the stress distribution in various parts of a scapula during normal physiological movements of the arm. The effect of the load transfer on individual parts of the scapula can be useful in understanding the basic mechanics of the scapula and can serve as the reference solution for comparing deviations in stress distribution, due to insertion of prosthesis. The overall reference model of the natural scapula is also useful in developing a submodel with glenoid prosthesis. Therefore, the development and stress analysis of the 3-D FE model of a normal scapula is an important sub-goal. Although both the computer models and the experimental validation have been used, the emphasis of this study lies on the development, validation and use of the 3-D FE model of the scapula. The later part of the sudy deals with stress analyses of cemented and uncemented glenoid prostheses, in order to understand the load transfer mechanism and to investigate the mechanical factors responsible for potential failure scenarios.

1.8 Structure of the book

The present study deals with a biomechanical analysis of stresses and strain in the scapula and the effect of application of glenoid prostheses with or without cement. In view of the complicated 3-D structure of the scapula, the FE method has been used as the basic tool for analysing stresses and strain. Experimental strain gage measurements on fresh scapulae were undertaken in order to validate the FE model of the scapula. The scope of each chapter of the book, which collectively contributes towards achieving the primary goal of this study, is presented in the following order.

Chapter 2 describes a study on the bone density and stiffness of scapula trabecular and compact bone from CT-scan measurement. In order to supply the FE model with realistic input data on density and elastic modulus, relationships between the CT gray values in Hounsfield Units, the apparent density and the elastic modulus were determined. Formulation of these relationships is based on experimental data of Frich (1994) and on the analytical structure of the trabecular and compact bone.

An elaborate description on the development of a 3-D FE model of the scapula is presented in Chapter 3. Quantitative CT-scan data have been used for realistic representation of geometry and material properties of the whole scapula. The musculoskeletal shoulder model of forces has been used as applied loading conditions for estimation of stresses in the scapula.

Chapter 4 deals with the experimental strain gage validation of the FE model of a fresh scapula, obtained from a donated cadaver. Eighteen strain gages were glued on the surface of the scapula, which was loaded on a mechanical testing machine. The measured strains and numerical FE strains for all the eighteen strain gages were compared for different load cases in order to obtain a thorough validation of the FE model of the scapula.

The FE model, developed in Chapter 3, has been used in Chapter 5 to study the load transfer in a natural scapula when it is subject to muscle, ligament and joint reaction forces. Using the static

musculoskeletal shoulder model, which includes all muscles, ligaments and joint reaction forces, during humeral abduction, stress distributions in the individual parts of the scapula were analysed.

In Chapter 6, sub-models of two fundamental cemented glenoid component designs (total polyethylene and metal-backed polyethylene) have been developed. These submodels were based on the overall reference solution of the natural scapula (Chapter 5). Using these 3-D FE models of the cemented glenoid prostheses, stress distributions in the individual components and at the material interfaces were obtained for the purpose of analysing design features and failure criteria.

Chapter 7 deals in another 3-D FE submodel model of the glenoid inserted with an uncemented metal-backed prosthesis. Similar to Chapter 6, the stress analysis of its individual components and the respective material interfaces were obtained for analysing failure criteria and exploring the possibilities of uncemented glenoid prostheses as compared to the cemented designs.

Finally, in Chapter 8, the significance and conclusions of the study, as a whole, is presented. Based on the results of each chapter, conclusions are drawn with regard to the motivation and goal of the study, as discussed in the preceding section. A retrospective review and recommendations for future research on improved of glenoid prostheses have been presented.