BIOMECHANICS OF BONE BLOCK PROCEDURES IN ANTERIOR SHOULDER INSTABILITY SURGERY

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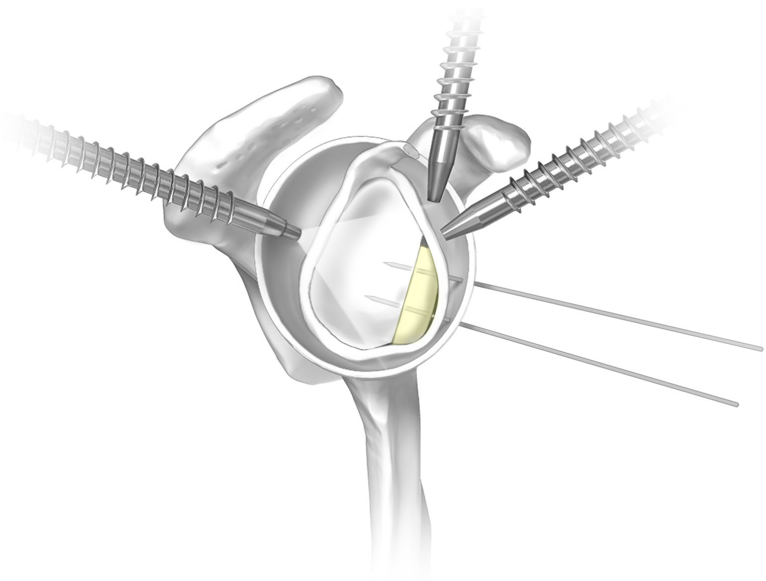
Combined doctoral and clinical orthopedic surgery and traumatology PhD program



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A thesis submitted in fulfillment
of the requirements for the degree
of Doctor of Philosophy

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2019

GHENT UNIVERSITY

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Addendum 2.1

Willemot L., Declercq G., Verborgt O. Revision of a Failed Latarjet Procedure Using an Open Tricortical Iliac Crest Autograft Technique. Techniques in Shoulder & Elbow Surgery. 16(3):69–73, SEP 2015. DOI: 10.1097/BTE.0000000000000052

Appendices

Appendix 1.
Curriculum Vitae

Appendix 2.
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Abbreviations

2D: Two-dimensional
3D: Three-dimensional
AbIGHL: Anterior Band Inferior Glenohumeral Ligament
AC: acromioclavicular
ALPSA: Anterior Labral Periosteal Sleeve Avulsion
AMBRI: Atraumatic, Multidirectional, Bilateral, Rehabilitation, Inferior capsular shift
AP: Antero-Posterior
AZ: Academisch Ziekenhuis
BSSR: Bony shoulder stability angle
CA: Congruent Arc
CAL: Coraco-Acromial Ligament
CC: Coraco-Clavicular
CHL: Coracohumeral Ligament
CLC: Capsulolabral Complex
CT: Computed Tomography
CS: Conjoint Sling
DTD: Distance to Dislocate
ETD: Energy to Dislocate
G: Glenoid
GHL: glenohumeral ligament
GLAD: Glenolabral Articular Disruption
H: Height
HAGL: Humeral Avulsion Glenohumeral Ligament
HERI: Humeral extension and internal rotation
HH: Humeral head
HR: Hazard Ratio
ICBG: Iliac Crest Bone Graft
IGC: Inferior Glenoid Circle
JFR: Joint Reaction Force
LSSC: Lower Subscapularis
MRI: Magnetic Resonance Imaging
OR: Odds Ratio
PbIGHL: Posterior Band Inferior Glenohumeral Ligament
PF: Peak Force
RI: rotator interval
ROC: Radius of Curvature
SC: sternoclavicular
SD: Standard Deviation
SI: Superio-inferior
SLAP: Superior Labral Tear from Anterior to Posterior
SSS: Subjective Shoulder Score
TL: Transverse Ligament

TUBS: Traumatic, Unilateral, Bankart lesion, Surgery
USSC: Upper Subscapularis
W: Width
WOSI: Western Ontario Shoulder Instability

Chapter 1: Introduction

“I plodded conscientiously through the twenty-six letters, and the only malady I could conclude I had not got was housemaid's knee.”

Jerome K. Jerome, Three Men in a Boat

Overview

This chapter outlines the research questions at the heart of this thesis and enumerates the specific aims of the work. Furthermore, the first chapter explores the phenomenon of shoulder instability with an emphasis on traumatic anterior shoulder dislocation. Definition, epidemiology, classification and risk factors are discussed as well as relevant anatomy and biomechanical mechanisms. A brief overview of clinical presentation and relevant imaging techniques is also given.

1.1 Background and Problem Statement

Anterior shoulder instability is a frequent problem, with an incidence between 21.9 and 56.3 per 100 000 person-years (Shields et al., 2017)(Liavaag et al., 2011)(Simonet et al., 1984)(Zacchilli and Owens, 2010). Half of these patients will not experience any further instability after the initial event (Hovelius et al., 2008). However, a greater risk of recurrent instability and symptomatology is present in the young, male, active patients, especially when presenting with bony injuries (Boileau et al., 2006)(Rhee et al., 2009). The role of patho-anatomical bony injuries, such as the bony Bankart and Hill-Sachs lesions, in early recurrence after standard capsulolabral repair is increasingly recognized (Boileau et al., 2006)(Randelli et al., 2012). In combination with the greater awareness of the detrimental long-term effects of recurrent shoulder dislocation, these findings have led to an upsurge in interest in surgical alternatives to the classic soft-tissue repair procedures (Hovelius et al., 2009)(Lädermann et al., 2013)(Gordins et al., 2015).

Thanks to the significantly lower recurrence rates of coracoid transfer procedures, the Bristow and Latarjet type surgeries have become the treatment modality of choice for high-demand patients presenting with shoulder instability and important glenohumeral bone loss (Allain et al., 1998)(Longo et al., 2014). So much so, that the indications have been expanded by some authors to include high-risk patients without bony glenoid deficiency. Conversely, several reports of high complication rates after coracoid transplantation have encouraged research into the adaptation and modification of existing techniques, in the hope of increasing efficiency and avoiding adverse events (Griesser et al, 2013)(Butt et al., 2012). Open and arthroscopic glenoid reconstructions using free iliac crest autografts, distal clavicle autografts, and tibial or glenoid osteochondral allografts have been described as viable treatment options. However, biomechanical data on the Bristow and Latarjet procedures is sparse and the influence of such modifications on overall shoulder stability is not well understood. Moreover, the theorized benefits have, to a large extent, not been verified scientifically. There exists a clear need to investigate the biomechanical principles of anterior glenoid bone graft procedures in the treatment of shoulder instability. Such an investigation would also shed light on the underlying reasons for failure after bone block procedures and explore the biomechanical potential of the novel graft sources and grafting techniques.

1.2 Aims

The general underlying aim of this doctoral work is to investigate whether it is possible to improve on the results of bone block procedures, and to reduce postoperative complications. Specifically, this thesis aims to explore the potential of free bone grafts to provide a valid alternative to the classic coracoid transfer procedures. To achieve this we have divided the work in a sequence of research questions. To start with, we will review the definition and meaning of "bone block surgery", describing both the historical and contemporary understanding of the relevant terms and eponyms. We will also try to place these procedures within the wider context of the treatment of shoulder instability (**1**). Furthermore, we will explore the current knowledge concerning the biomechanical mechanisms behind the success of anterior glenoid bone grafting (**2**). Specifically, we will endeavour to answer a pertinent clinical question related to the usefulness of free bone grafts in glenoids without glenoid bone loss. To ascertain this, we will perform a biomechanical study investigating the biomechanical soundness of free bone grafting in intact glenoids after the creation of an anterior labral tear (**3**). In continuation of this line of investigation, and aided by the knowledge gained from the first cadaveric experiment, we will seek to elucidate whether translational stiffness of glenoid reconstructions, as tested biomechanically, can be deduced theoretically from surface characteristics (**4**). Next, we will expand our research into the role of joint surface morphology by comparing the surface characteristics of various commonly used bone grafts. To this end, we will first perform an inventorizing review of the various classic and novel graft types for the reconstruction of anterior glenoid bone defects (**5**). Afterwards, we will seek to evaluate the morphological profile of relevant graft types in order to determine which grafts might be promising from a biomechanical standpoint (**6**). Moreover, this thesis aims to reduce the postoperative failures and complications associated with traditional bone block procedures. In particular, we will investigate whether free bone grafts pose a smaller risk of postoperative complication. In order to achieve this, we will first inventorize and review the current literature on this topic (**7**). It is well established that the most common postoperative complications and indications for revision after bone block procedure are related to hardware failures. Therefore, we will perform a biomechanical test of commonly used screws for graft fixation (**8**). A brief summary of the research questions organized per chapter is given below.

Are free bone grafts a valid alternative for classic bone block procedures?

Chapter 1:	Introduction
Chapter 2:	What is bone block surgery? (**1**)
Chapter 3:	What are the biomechanical principles behind bone grafting procedures? (**2**) Is free iliac bone grafting of an intact glenoid biomechanically sound? (**3**) Is translational joint stiffness predictable based on joint surface characteristics? (**4**)

Chapter 4: What are the different graft options in cases of bony instability? (**5**)
What is the morphological profile of various graft types? (**6**)

Why do traditional bone block procedures fail?

Chapter 5: Incidence and nature of failures after bone block procedures (**7**)
Biomechanical role of hardware in the graft fixation? (**8**)
Chapter 6: Conclusions

The attractiveness of free bone grafting procedures is partly derived from the wide selection of available graft types, ease of graft harvesting, limited or absent donor morbidity, customizability of graft shape and size, possibility of simple all-arthroscopic techniques, graft passage through the rotator interval without disturbing the subscapularis muscle, and overall anatomic nature and minimal invasiveness of the procedure (Verborgt et al., 2015). However, further scientific exploration is required to evaluate the biomechanical and clinical behaviour of free bone block grafting in recurrent shoulder instability. These questions can be summed up in the hypothesis of this doctoral work: "Free bone blocks are a valid, and in some cases preferred, alternative to traditional coracoid based anterior grafting techniques".

1.3. Shoulder instability

1.3.1 Definitions

Instability of the shoulder is a double misnomer. The "shoulder joint" is not a single articulation, but a complex structure composed of three bones, three joints and a gliding junction. The ball-and-socket joint connecting the shoulder blade and upper arm is typified by a large mismatch between the articular surfaces. The glenoid socket covers only a third of the surface of the humeral head (Soslowksy et al., 1992). This discrepant configuration awards the glenohumeral joint the largest range of motion of any joint in the human body. However, the generous mobility is accompanied by an inherent risk of "instability". In mechanical terms, instability is the property of a joint not returning to its original position after a perturbation. In the clinical setting such a situation is best compared to a dislocation, whereas clinical instability may refer to either a complete dislocation or an excessive articular displacement known as a subluxation (Fig. 1) (Veeger and Vander Helm, 2007). Matsen et al. defined shoulder instability as "a clinical condition in which unwanted translation of the humeral head on the glenoid compromises the comfort and function of the shoulder." (Matsen et al., 1991). Hyperlaxity and instability are sometimes, wrongly, used interchangeably. Hyperlaxity is defined as an increase in length and elasticity of the normal joint restraints, resulting in a clinically detectable increased range of motion and distractibility. Hyperlaxity is caused by more elastic connective tissue, which may be part of a benign congenital hypermobility syndrome, or it may be the result of an acquired ligament stretching, or associated with an underlying genetic disease. Hyperlaxity in the shoulder is not considered pathological in itself. However, hyperlax patients are at greater risk of recurrent instability after injury as described further on.

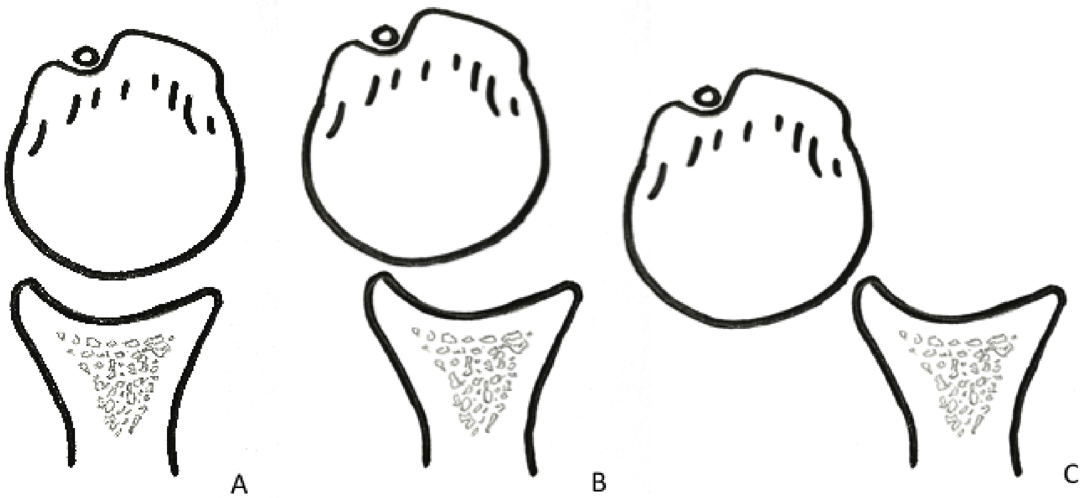

Figure 1.1 Schematic drawing of a glenohumeral joint in various configurations; A. Normal glenohumeral alignment; B. Anterior subluxation of humeral head; C. Anterior dislocation of the humeral head.

1.3.2 Epidemiology

Overall reported incidence of glenohumeral instability requiring emergency room attention in Western Europe has varied between 21.9 cases per 100 000 person-years in the United Kingdom (Shields et al., 2017) and 56.3 cases per 100 000 person-years in Scandinavia (Liavaag et al., 2011). Similar numbers have recently been reported in the United States, where a large-scale epidemiological study found an incidence of 23.9 cases per 100 000 person-years in the general population, almost twice the reported incidence in classically cited literature (Simonet et al., 1984)(Zacchilli and Owens, 2010). The shoulder is the most commonly dislocated joint in adults, distantly followed by the elbow at a rate of 5.2 per 100 000 person-years (Stoneback et al., 2012). Epidemiological studies reveal a significant burden of disease, yet reported incidences of shoulder instability are believed to be underrepresentative. Epidemiological surveys lack the capability of recording those cases which do not seek professional medical attention. Specifically, glenohumeral subluxations often remain unreported, despite evidence that this type of instability may constitute the majority of instability cases (Owens et al., 2007). The incidence of shoulder instability is traditionally believed to be the greatest in young and active populations, although a second peak exists in older women and elderly men (Shields et al., 2017). The highest incidences, with reported rates of 0.12 to 0.22 incidents per 1000 athlete-exposures, are found in collegiate and high school athletes respectively (Robinson et al., 2012)(Owens et al., 2009). Similarly, considerably higher dislocation rates are observed in active duty military service members compared to the general population. Reported incidences vary between 169 per 100 000 person-years in the general military personnel and 435 per 100 000 person-years in younger military cadets (Owens et al., 2009).

1.3.3 Types of Instability

Traditionally, glenohumeral instability has been classified according to etiology. Most authors draw a distinction between "traumatic" and "atraumatic" instability. The majority of cases are traumatic and result from damage to the stabilizing structures of a previously intact shoulder. In 5% of cases, instability arises without significant trauma and is due to an inherent insufficiency of the shoulder stabilizing mechanisms (Burkhead and Rockwood, 1992). Additionally, shoulder instability is often categorized according to the direction of translation during instability. Most frequently, the humeral head translates anteriorly, resulting in subclavicular, subcoracoid or subglenoid dislocation (Gloss, 1988). Conversely, the humeral head sometimes translates posteriorly, which occurs at a rate of 1.1 per 100 000 person-years in the general population and is thus significantly less common than anterior instability (Robinson et al., 2011). Nevertheless, posterior shoulder instability has been shown to constitute up to 10% of glenohumeral dislocations in a young and active patient population (Owens et al., 2007). Rare cases of pure inferior translation in abduction may result in "luxatio erecta", in which the patient cannot lower the arm from its abducted position. Such inferior dislocations have a reported incidence of less than 0.5% (Brady et al., 1995). Patients exhibiting symptoms of instability in more than one direction are typically not associated with traumatic shoulder injury. These patients are referred to as "multidirectionally unstable", a term coined by Neer and Foster in 1980 (Neer and Foster, 1980).

Alternatively, glenohumeral instability can be classified according to chronology. Acute instability is differentiated from chronic injury, and isolated symptoms from recurrent shoulder instability. The severity of instability is often defined as either subluxating of dislocating, depending on the degree of translation and the ability to spontaneously reduce. Finally, abnormal muscle patterning should be taken into account when classifying shoulder instability. Moroder and colleagues classified these patients as suffering from functional shoulder instability. In this category, patients exhibit glenohumeral instability due to pathological activation of specific muscle groups around the shoulder in the absence of significant structural lesions. Within this group, certain patients may exhibit the need to position the arm in a particular provocative position, in which case it is termed positional instability (Moroder et al., 2019). A careful distinction should be made between voluntary and involuntary positional instability in regards to the intentionality of the patient to elicit the symptoms. Moroder classified these as "controllable" and "uncontrollable" functional instabilities. The term "habitual dislocation" has confusingly been used in the past to denote both voluntary and involuntary recurrent instability and should be avoided. Alternatively, it has been suggested to use the word "volitional" and "demonstrable" to differentiate between intentional instability with and without underlying secondary gains or psychological pathology respectively (Kuhn, 2009).

1.3.4 Classifications

Classical teaching divides patients in two categories depending on a number of characteristics. The first type is known by the acronym "TUBS" (Traumatic, Unilateral, Bankart lesion, Surgery) and consists of patients with unilateral shoulder instability after an injury, with specific patho-anatomical findings, and requiring stabilization surgery. The second type is termed “AMBRI” (Atraumatic, Multidirectional, Bilateral, Rehabilitation, Inferior capsular shift) and consists of those patients with bilateral symptoms, without a history of significant trauma, in whom conservative treatment is the mainstay except in rare refractory cases, in which a specific capsular shift procedure is recommended (Thomas and Matsen, 1989). Although clinically useful, this system represents only two extremes of the instability spectrum. Gerber and Nyfeller have since proposed an improved classification distinguishing between static, dynamic and voluntary instability. In class A, static instability, is assessed radiographically and associated with degenerative joint disease and rotator cuff injury. This type of instability goes beyond the scope of the thesis and will not be discussed further. In the dynamic or class B instability, the authors differentiate between chronic locked anterior or posterior instability (B1), unidirectional instability without hyperlaxity (B2), unidirectional instability with hyperlaxity (B3), multidirectional instability without hyperlaxity (B4), multidirectional instability with hyperlaxity (B5) and uni- or multidirectional instability with voluntary reduction (B6). Voluntary instability is given a separate category (Class C). The authors noted that the B2 and B3 groups constituted 60% and 30% of the traumatic instability population, whilst the B4 category was extremely rare and B5 represented only 5% of shoulder instability patients (Gerber and Nyfeller, 2002).

Classification	**Substance**	**Source**
Direction	Anterior Posterior Inferior Multidirectional	
Traumatic vs. Atraumatic	Traumatic Unilateral Bankart Surgery (TUBS) vs. Atraumatic Multidirectional Bilateral Rehabilitation Inferior Capsular Shift (AMBRI)	Thomas and Matsen, 1989
Static vs. Dynamic	<u>Class A: static instability</u> <u>Class B: instability</u> Chronic locked instability (B1) *Unidirectional* instability without hyperlaxity (B2) *Unidirectional* instability with hyperlaxity (B3) *Multidirectional* instability without hyperlaxity (B4) *Multidirectional* instability with hyperlaxity (B5) Voluntary reduction (B6) <u>Class C: voluntary instability</u>	Gerber and Nyfeller, 2002
Traumatic vs. Patterning	Stanmore Polar system	Kessel and Bayley, 1986

	Polar I Traumatic, structural injury, no patterning Polar II Less defined trauma, some injury, some patterning Polar III No trauma, no injury, patterning	
Comprehensive (ABC)	A First time A1 Subluxation A2 Dislocation B Dynamic B1 Functional B2 Structural C Static C1 Constitutional C2 Acquired	Moroder and Scheibel, 2018
Comprehensive (FEDS)	Frequency Etiology Direction Severity of symptoms	Kuhn et al., 2010

Table 1.1
Overview of classification and categorization systems for shoulder instability.

In another attempt to shed light on the continuity of shoulder instability, the Stanmore system was recently reintroduced (Fig. 2). This system defines three separate categories. Polar type 1 are patients with a defined history of trauma, unidirectional instability and a Bankart-type lesion. Polar type 2 patients present with a less defined history of recent trauma, are likely to exhibit a structural lesion and have an overlay of abnormal muscle recruitment. Polar type 3 patients have no history of trauma, no structural abnormalities and may be voluntary dislocators or exhibit significant muscle recruitment pattern abnormalities. The three polar types are not constrained categories, yet form the corners of the so-called “Bayley” triangle enclosing a continuous area on which the instability can be situated (Kessel and Bayley, 1986). Ongoing assessment is required to recognize changes along the triangles’ axes and implement appropriate changes in therapeutic management (Lewis et al., 2004).

Recently, a new and entirely patient reported classification system was proposed by Kuhn et al., based on frequency, etiology, direction and severity of symptoms (FEDS) (Kuhn, 2010). Despite the simplicity and psychometric attractiveness of the classification, it has not yet gained widespread use. Similarly, Moroder and Scheibel published a comprehensive classification system for posterior shoulder instability based on first-time (A), dynamic (B) or static (C) presentation. First time dislocators are further divided in subluxations (A1) or dislocations (A2), dynamic instabilities are carved up in functional (B1) or structural problems (B2), while static instability is divided up in constitutional (C1) or acquired (C2) forms

(Moroder and Scheibel 2018). This system has not yet achieved popularization due to it relatively recent publication.

There is currently no satisfactory all-encompassing classification system for shoulder instability due to the complexity and diversity of presentation. The lack of uniformity in definition and classification is a hindrance in the development of unambiguous treatment guidelines and in the communication between physicians or researchers. An overview of the most useful systems is given in table 1.1.

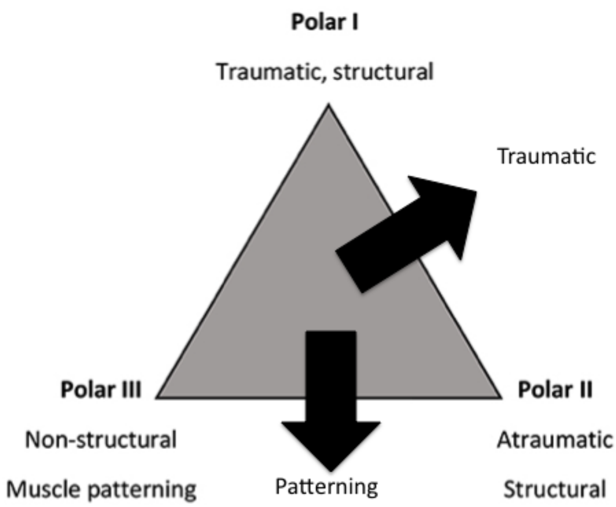

Figure 1.2
Illustration of the Stanmore system. The system assigns patients to Polar I: traumatic injury with a structural lesion; Polar II: less defined trauma with a structural lesion; and Polar III: atraumatic without structural lesion, yet with muscle recruitment abnormalities.

1.3.5 Risk Factors

It has traditionally been reported that individuals in the second and third decades of life are at the greatest risk of an acute instability event (Zacchilli and Owens, 2010)(Leroux et al., 2015). However, more recent literature has exposed a bimodal distribution in the male population with a peak between 15 and 44 years of age and in the very elderly (>85 years)(Fig. 1.3). Conversely, in the female population a peak has been described in patients over 50 years old (Shields et al., 2017)(Shah et al., 2017). Greater scientific attention has historically been given to the treatment of younger patients due the higher risk of ensuing recurrent instability. Studies have shown that 50% of patients under the age of 27, and 77% of those under 18 years old will develop recurrence within the first two years after an initial instability event (Mather et al., 2011)(Robinson et al., 2006)(Te Slaa et al., 2004). Acute glenohumeral instability in patients older than 40 carries less risk of recurrence, yet is associated with rotator cuff tears, fractures, as well as vascular and neurological injury (Paxton et al., 2014). Evaluation and treatment of this subcategory is profoundly different from anterior shoulder instability in the younger population and goes beyond the scope of this thesis.

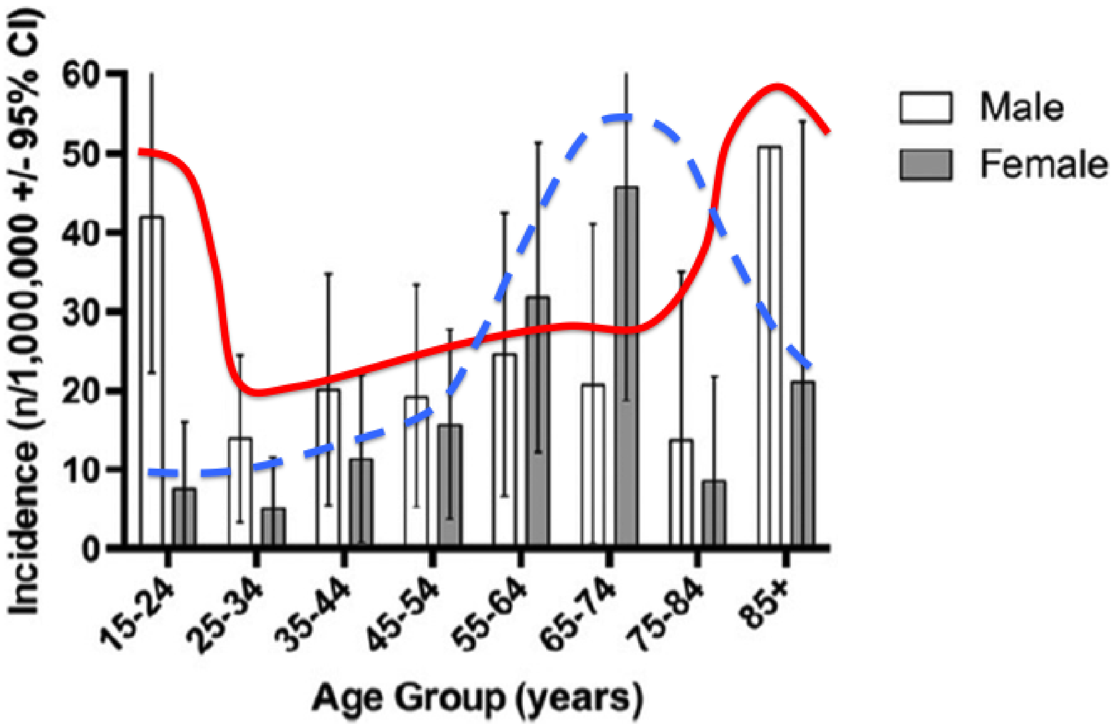

Figure 1.3 Incidence of glenohumeral dislocation in the general population. A bimodal distribution is seen for males with a peak in the 15-24 and 85+ year age categories (red curve), while in females a unimodal distribution is seen peaking in the 65-75 age category (blue dashed line). Adapted from Shields et al., *Epidemiology of glenohumeral dislocation and subsequent instability in an urban population.* Journal of Shoulder and Elbow Surgery, 2017).

Despite widespread agreement in the literature concerning the higher risk of male individuals for shoulder instability (Owens et al., 2009)(Leroux et al., 2015), emerging data has indicated that female athletes participating in high-risk sports with the same exposure may approach similar risk levels (Peck et al., 2013)(Owens et al., 2009). However, due to societal differences, males still carry the greatest burden of disease. Sports participation, especially contact sports and overhead sports, may predispose to a higher risk of recurrence (Sachs et al., 2007)(Robinson et al., 2006). Prior instability has long been recognized as a predictor of future instability (Cameron et al., 2013)(Lee et al., 2018). Concomitant medical conditions such as epilepsy may also predispose to shoulder instability. Seizures are traditionally associated with posterior instability, yet anterior instability is found in more than half of epileptic instability patients (Buhler et al., 2002)(Thangarajah et al., 2015). Anatomical and morphological differences may also increase the risk of anterior shoulder instability. Peltz et al. reported significantly more shallow glenoids in patients with glenohumeral instability after analyzing articular curvature in an unstable population (Peltz et al., 2015). Similarly, Owens et al. demonstrated that patients with taller and more narrow glenoids, and those with a greater coracohumeral distance on axial imaging, were at higher risk of developing shoulder instability (Owens et al., 2014). Likewise, several authors have shown a direct association between increased glenoid anteversion and shoulder instability (Aygun et al., 2016)(Hohman and Tetsworth, 2015). In a recent publication based on statistical shape modelling, Jacxsens and colleagues concluded that unstable shoulders tended to have coracoids which were more likely to be shorter and medially oriented, with an overall more posteriorly rotated coraco-acromial arch (Jacxsens et al., 2019). Such studies point to significant bony differences between stable and unstable shoulders.

Patho-anatomical changes such as capsulolabral and osseous injuries are known to significantly increase the risk of recurrence (Balg and Boileau, 2007). The influence of this type of lesions is discussed in more detail further on. Patients exhibiting joint hyperlaxity are also at a greater risk of shoulder instability. Hyperlaxity is frequently seen in athletes due to the competitive advantages it provides. However, the weaker supportive and stabilizing structures may be exposed to excessive chronic or acute stress during athletic performance, leading to structural damage and instability (Johnson et al., 2010). Generalized and, in particular, shoulder hyperlaxity are considered risk factors for recurrent shoulder instability (Balg and Boileau, 2007). Balg and Boileau devised the Instability Severity Index Score (ISIS) after analysis of failures following Bankart repair. The ISIS is a useful tool based on patient's age, physical activity, hyperlaxity and glenohumeral bone loss. Patients younger than 20 years old, with glenoid loss of contour or Hill-Sachs on external rotation x-ray, and patients involved in competitive sports earn 2 points for each risk factor. Contact sports and hyperlaxity can each contribute another point for a total of 10 points. The ISIS helps decision making in the choice between soft-tissue repair and anterior glenoid bone grafting (Balg and Boileau 2007). The tool was independently validated recently by Phadnis and colleagues when they demonstrated a failure risk after Bankart repair of 70% in cases with an ISIS higher than 4 and only 4% in those with a lower score (Phadnis et al., 2014). The authors also found glenoid and humeral bone loss to be the most influential factors in the risk analysis. A condensed overview of the most relevant risk factors for recurrent shoulder instability is given in table 1.2.

Risk Factor	Categories	Risk	Source
Age	< 40 years old > 40 years old	+++	Olds et al., 2015
Sex	Males Females	+/-	Olds et al., 2015
Sports	Contact sports	+	Sachs et al., 2007
	Type of sports	+	Robinson et al., 2006

Prior Injury	Prior instability	+++	Cameron et al., 2013
Hyperlaxity	Hyperlaxity	++	Robinson et al., 2006; Cameron et al., 2013; Boileau et al., 2006
Soft-tissue injury	ALPSA lesion	++	Ozbaydar et al., 2008
Laterality	Dominance	0	Lim et al., 2018; Boileau et al., 2006
Bony lesions	Glenoid bone loss	+++	Shaha et al., 2016; Shin et al., 2016
	Glenoid fracture (fragment)	0	Boileau et al., 2006
	Glenoid fracture	protective	Olds et al., 2015
	Hill-Sachs lesion	++	Olds et al., 2015; Boileau et al., 2006
	Combined (bipolar lesion)	++++	Robinson et al., 2006; Lee et al., 2018, Shaha et al., 2016
	Tuberosity fracture	protective	Olds et al., 2015
Anatomy	Glenoid index	+++	Owens et al., 2014
	Coracohumeral distance	+	Owens et al., 2014
	Version	+	Hohman and Tetsworth, 2015
	Coraco-acromial arch rotation	+	Jacxsens et al., 2019
Nerve injury	Nerve palsy	++	Olds et al., 2015
Other	Epilepsy	+++	Bühler and Gerber, 2002

Table 1.2. Risk factors for recurrent dislocation. The symbols denotes a risk increase of 2 (+), 2-5 (++), 5-10 (+++) or more than 10 times the average recurrence rate. The (+/-) refers to ambivalence surrounding a particular risk factor. A (0) indicates no influence on risk.

1.4 Anatomy

1.4.1 The Shoulder Complex

The shoulder complex consists of three bones; the humerus, the scapula and the clavicle. These bones articulate with each other and the torso through the glenohumeral, acromioclavicular (AC) and sternoclavicular (SC) joints as well as the scapulothoracic and subacromial gliding planes (Fig. 1.4)(Culham and Peat, 1993).

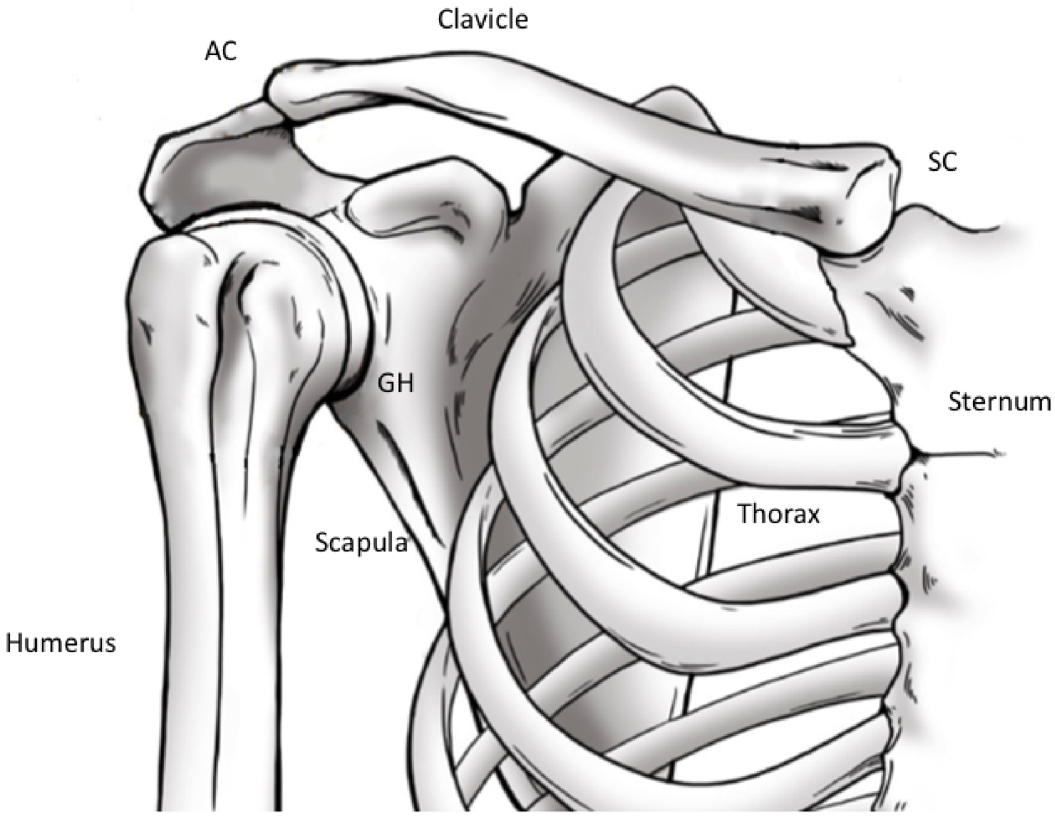

Figure 1.4 Drawing of the thorax and the three bones of the shoulder complex. The humerus, scapula and clavicle articulate with the thorax via the sternoclavicular (SC) and thoracoscapular joints. The scapula articulates with the humerus through the glenohumeral

joint (GH) and with the clavicle through the acromioclavicular joint (AC). Adapted from J. W. Giles doctoral thesis 2014 with permission.

1.4.2 Osseous Structures

The scapula forms the main connection between the upper limb and the axial skeleton. The thin triangular bone has no ligamentous or bony attachment to the torso except via the clavicular AC and SC joints. The scapula serves several important roles. It provides the main attachment site for multiple muscles involved in shoulder motion including the thoracoscapular muscles inserting on the shoulder blade and controlling scapular motion and position, and the scapular muscles inserting on the humerus and forearm, responsible for glenohumeral motion and stability. The scapula additionally acts as a moveable platform stabilizing and supporting the upper limbs weight during motion and extending the limbs' range of motion via thoracoscapular gliding (Lippitt and Matsen, 1993). The scapular spine or spinous process originates from the medial scapular margin and increasingly projects posteriorly as it moves laterally and superiorly. The spine divides the supra from the infraspinatus fossa and extends laterally as the acromion. The acromion projects anterosuperiorly to form an arc of bone over the humeral head and articulates with the lateral clavicular end at the AC joint. The coracoid process is a hook-like bony protrusion at the anterior and lateral side of the scapula. From its base, the coracoid projects anteriorly and subsequently curves laterally at the so-called "elbow". The coracoid serves as a critical anchoring point for several tendons and ligaments as detailed below (Culham and Peat, 1993). One of the most important features of the scapula is the shallow pear-shaped glenoid fossa at its lateral aspect. The glenoid ranges between 32.6 and 39 mm in height, and has a mean width of 28.3 mm. Women tend to have slightly smaller glenoids than men (Strauss et al., 2009). The glenoid is covered by hyaline cartilage which is believed to thicken at the periphery, thus deepening the glenoid socket (Soslowsky et al., 1992). However, a more recent in-vivo study has disputed this claim, reporting a more uniform cartilage distribution (Schleich et al., 2017). The cartilage may be completely absent in the center of the glenoid, in a well-defined zone known as the "bare spot". This is not seen during fetal development and is considered an acquired variation related to continued humeral contact (DePalma, 1949)(Kim et al., 2010). The anatomical value of the bare spot as the center of the inferior glenoid is debated as discussed in the imaging section. The glenoid is deepened and broadened by a ring of fibrous tissue named the labrum. The labrum also serves as the scapular attachment site for the glenohumeral ligaments as detailed in the next subchapter. Glenoid orientation exhibits considerable variation between individuals, yet an upward tilt of 5-7 degrees and a glenoid version between 9 degrees retroversion and 2 degrees anteversion is typically reported (Friedman et al., 1992)(Mallon et al., 1992)(Bokor et al., 1999)(Kwon et al., 2005)

The clavicle is an S-shaped bone in the axial plane that connects the scapula to the torso via the AC joint laterally and the SC joint medially. The clavicle acts as a strut during mechanical loading of the arm and maintains separation between the scapula and the ribcage. This distance is critical for the optimal function of thoracoscapular and thoracohumeral muscles. The clavicle serves as an important attachment site for several muscle groups and plays a major role in scapular kinematics (Culham and Peat, 1993)(McClure et al., 2001).

The humerus is the long bone connecting the clavicle and scapula to the forearm bones. The proximal epiphysis, colloquially known as the humeral head, contains the articular surface which faces superiorly, medially and posteriorly. The average angle between the humeral head and shaft lies between 130° and 150°, while the mean humeral retroversion is estimated to lie between 6.7° and 47.5° (Cyprien et al., 1983)(Pearl and Volk, 1996)(Walch and Boileau, 1997). Anatomical studies have revealed that although the central part of the humeral head is spherical, the periphery is actually elliptical (Iannotti et al., 1992). Cartilage distribution on the humeral head has long been thought to be complementary to the glenoid distribution by thickening at the centre (Soslowsky et al., 1992)(Zumstein et al., 2014). However, this concept has been disputed in a more recent *in-vivo* study which reports a more or less uniform cartilage distribution (Schleich et al., 2017). The humeral head does exhibit a number of important anatomical features. The lesser and greater tuberosities are the bony prominences separated by the bicipital groove. The humeral tuberosities are situated just laterally to the epiphysis, with the lesser tuberosity lying anterolaterally and the greater tuberosity posterolaterally to the articular surface. An area devoid of cartilage can be found between the articular surface and the posterolateral cuff insertion which is termed the bare area. This is a non-pathological age-related acquired finding (DePalma, 1949). The tuberosities serve as insertion points for the rotator cuff muscles as described below, and are separated by the bicipital groove which contains the long head of biceps tendon. The bony lips on either side of the groove serve as attachment sites for major muscle groups such as the pectoralis major, latissimus dorsi and teres major (Taylor et al., 2015).

1.4.3 Joint Capsule and Ligaments

The joint capsule is a thin membrane which surrounds the synovial articular surfaces. Medially the capsule blends into the glenoid labrum, while laterally the capsule attaches to the articular margin of the humeral head. Posteriorly the capsule is reinforced by the infraspinatus and teres minor tendons and anteriorly by the subscapularis tendon and glenohumeral ligaments (GHL). These ligaments exhibit great variability in their morphology. However, in general the superior and middle GHLs originate between the supraglenoid tubercle and the base of the coracoid. The superior GHL inserts just superior to the lesser tuberosity, in the bicipital groove, and as fibers of the transverse humeral ligament. The middle GHL may be absent in 27% of cases, but when present inserts on the anterior aspect of the anatomical neck (Burkhart and Debski, 2002). The inferior GHL originates at the inferior glenoid neck or labrum and inserts on the inferior humeral neck. The ligament is subdivided in an anterior band, an axillary pouch and a posterior band. The anterior band is typically located between the 2 and 4 o'clock positions on the glenoid face and the posterior band is found between the 7 and 9 o'clock positions. The three parts act in unison to form a supportive hammock for the humeral head during rotation and abduction (Fig. 1.5) (Burkart and Debski, 2002)(O'Brien et al., 1990)(O'brien et al., 1995).

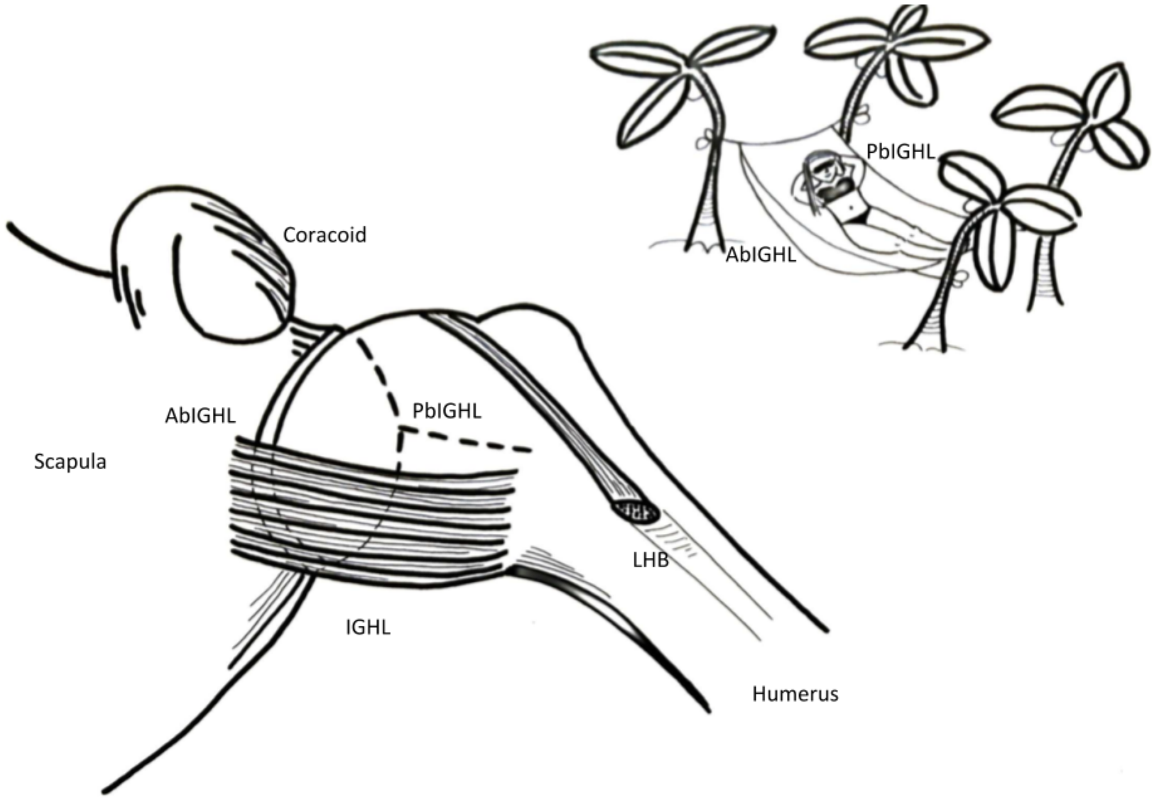

Figure 1.5 Inferior glenohumeral ligament (IGHL) complex. The anterior (AbIGHL) and posterior bands (PbIGHL) of the inferior glenohumeral ligament complex form a supportive hammock in which the humeral head is cradled during rotation and abduction. The comparison with a standard hammock with four fixation points is made in the cartoon. Tearing of the anterior band at the glenoid side, the humeral side or midsubstance will cause the figure to fall from the hammock. Similarly, after dislocation a persistent ligamentous injury may cause recurrent instability.

Furthermore, the fasciculus obliquus described by Delorme (Delorme., 1910) has been recognized as the spiral GHL. This ligament courses from the inferior part of the glenoid to the upper subscapularis insertion. Its exact biomechanical function is still under investigation (Merila et al., 2008). Glenohumeral ligaments are capsular thickenings, and are therefore best visualized from an intra-articular perspective. However, the macroscopic appearance of folds should not be mistaken for the location of the actual ligaments (Pouliart and Gagey, 2005). The transverse ligament runs between the lesser and greater tuberosity and stabilizes the bicipital tendon in its groove. The coracoacromial ligament connects the distal and lateral part of the coracoid process to the medial and anterior part of the acromion. Together these structures form the coracoacromial arch which articulates with the humeral head and prevents superior migration. The coracohumeral ligament arises from the lateral side of the base and horizontal limb of the coracoid below the coracoacromial ligament. The ligament runs through the so-called rotator interval (RI) between the subscapularis and supraspinatus tendon and inserts on the greater and lesser tubercle and in the bicipital groove. Its biomechanical function is disputed (Arai et al., 2014). The coracoclavicular ligaments connect the base of the coracoid to the undersurface of the clavicle and are divided in the trapezoid laterally and conoid ligament medially. The acromioclavicular ligaments reinforce the AC joint capsule. The biomechanically most critical ligaments are found superiorly and posteriorly (Rios et al., 2007)(Fig. 1.6).

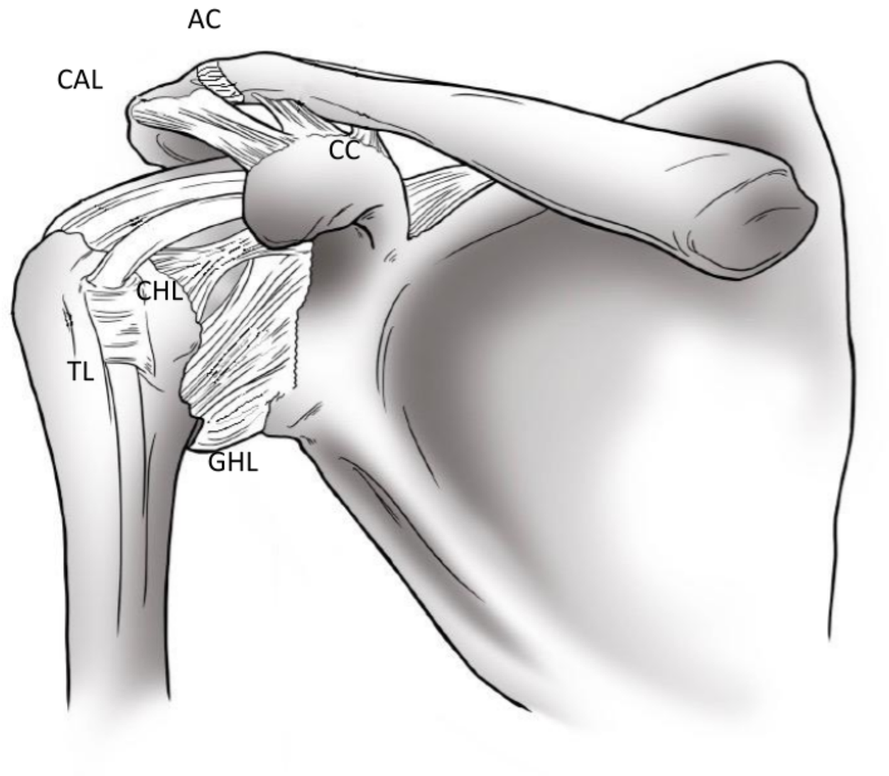

Figure 1.6
External view of the ligaments of the shoulder complex. These include the coracoclavicular ligaments (CC), the coracoacromial ligaments (CAL), the acromioclavicular ligaments (AC), the glenohumeral ligaments (GHL), the coracohumeral ligament (CHL) and transverse ligament (TL). Adapted from J. W. Giles doctoral thesis, 2014 with permission.

1.4.4 Muscles

A large number of muscles are responsible for the motion and stability of the shoulder complex. They are typically divided in scapulohumeral, scapulothoracic, thoracohumeral and biarticular muscle groups.

The scapulohumeral muscles originate on the scapula and insert on the humerus. These muscles therefore play an important role in glenohumeral motion and stability. The muscles belonging to this group are the deltoid, supraspinatus, infraspinatus, teres minor, teres major, subscapularis and coracobrachialis. The deltoid muscle is composed of an anterior, middle and posterior part. These parts have their origins on the clavicle, acromion and spine respectively, and converge towards the deltoid tuberosity on the proximal lateral side of the humeral shaft. The subscapularis, supraspinatus, infraspinatus and teres minor tendons blend with the joint capsule and the GHLs to form the rotator cuff. Only the inferior part of the rotator cuff lacks reinforcement by a muscle tendon. The rotator cuff muscles are independently innervated, yet tend to act in a concerted fashion. Moreover, due to the confluence at the insertion sites, activity of one muscle may influence passive tension in another area (Soslowsky et al., 1997). The supraspinatus muscle originates at the supraspinatus fossa between the spina and the superior scapular edge, and inserts on the greater tuberosity. The infraspinatus muscle originates at the infraspinatus fossa and inserts on the posterior part of the greater tuberosity. The teres minor and major both originate at the medial scapular edge, but where the teres minor blends with the infraspinatus, the teres major inserts on the anterior humeral shaft. The subscapularis muscle originates at the subscapularis fossa on the anterior face of the scapula and inserts on the lesser tuberosity. The coracobrachialis muscle originates at the tip of the coracoid process and inserts on the anteromedial humeral shaft (Rockwood and Matsen, 2009).

The scapulothoracic muscles originate on the torso and insert on the scapula. The muscles of this group include serratus anterior, trapezius, levator scapulae, minor and major rhomboids and pectoralis minor. The serratus anterior originates on the anterolateral rib cage and inserts on the anterior side of the medial scapular margo. The major and minor rhomboid muscles and levator scapula originate on the posterior cervical and thoracic vertebrae and insert on the posterior medial scapular margo. The trapezius muscle has a large origin on the posterior spinal elements from the occiput to the lower thoracic vertebrae and is typically divided in an upper, middle and lower third. These parts respectively insert on the lateral clavicle, acromion and scapular spine. The pectoralis minor muscle originates on the anterior rib cage and inserts on the medial side of the horizontal part of the coracoid process (Rockwood and Matsen, 2009).

The muscles connecting the torso with the humerus are the pectoralis major and the latissimus dorsi. The pectoralis originates on the medial half of the clavicle and sternum and inserts on the lateral lip of the bicipital groove. The latissimus dorsi has a wide origin on the lower thoracic and upper lumbar vertebrae, the iliac crest, the inferior three ribs, the inferior angle of the scapula and inserts on the medial bicipital lip and groove floor (Rockwood and Matsen, 2009).

The short and long head of the biceps brachii as well as the triceps brachii muscles cross more than one joint. The triceps long head originates at the inferior glenoid tubercle and crossed both the glenohumeral and elbow joints before inserting on the ulna. The short head of the biceps originates at the tip of the coracoid, whereas the long head originates at the supraglenoid tubercle before exiting the joint through the bicipital groove. Both heads blend together as one muscle at the level of deltoid insertion before inserting on the radial tuberosity.

1.4.5 Neurovascular anatomy

Most of the innervation of the shoulder is supplied by the brachial plexus. The brachial plexus is an intermeshing network of nerves arising from the fifth cervical to the first thoracic spinal nerve roots. The roots combine to form the upper, middle and lower truncus which in turn branch off anterior and posterior divisions to form the lateral, posterior and medial cords. The cords then finally branch off in the musculocutaneous (lateral cord), ulnar (medial cord), median (lateral and medial cord), as well as radial and axillary nerves (posterior cord) (Shin et al., 2005). The upper and lower subscapular nerves, as well as the the thoracodorsal nerve, branch off the posterior cord to innervate the subscapularis and teres major muscle. The axillary nerve is one of the two final branches of the posterior cord and unlike the radial nerve, it passes through the quadrilateral space formed by the long head of triceps, the teres minor and major and the humerus, to innervate the teres minor and deltoid muscles and supply sensation to the lateral proximal arm (Cahill and Palmer, 1983). The musculocutaneous nerve, one of the terminal branches of the lateral cord, pierces and innervates the coracobrachialis muscle at a distance of 3.1-8 cm from the coracoid process and goes on to supply the brachialis and biceps muscles innervation and provide sensation to the anterolateral forearm (Flatow et al., 1989). Although some smaller branches may enter the muscle more proximally (Klepps et al., 2001). The suprascapular nerve branches off the superior truncus and courses along the omohyoid muscle until it passes through the suprascapular notch to innervate the supraspinatus muscle. The nerve then runs around the spinoglenoid notch to innervate the infraspinatus muscle. The dorsal scapular nerve stems from the fourth or fifth cervical root and supplies the levator scapulae and rhomboid muscles. The pectoralis major and minor muscles are innervated by the medial and lateral pectoral nerves branching of the medial and lateral cords respectively. The latissimus dorsi is innervated by the thoracodorsal nerve which stems from the posterior cord, between the upper and lower subscapular nerves. Lastly, the accessory nerve (XI cranial nerve) supplies the trapezius muscle, and the long thoracic nerve which originates directly from the upper cervical roots, supplies the anterior serratus muscle (Shin et al., 2005).

The major arterial axis bears three different names along its course through the shoulder region. Medially to the first rib it is called the subclavian artery, between the lateral edge of the first rib and the branching off of the profunda brachii artery it is known as the axillary artery, and distally from this point it is termed the brachial artery. The transverse cervical and suprascapular arteries branch off of the thyrocervical truncus on the subclavian artery. The transverse cervical artery supplies the trapezius, while the suprascapular artery runs above the transverse ligament and suprascapular nerve to supply the supraspinatus muscle. The dorsal scapular artery branches from the subclavian artery to supply the rhomboids. Many anatomical variants have been described in this area. The thoracoacromial trunk arises from the axillary artery, deep to the pectoralis minor. The axis gives off the deltoid, pectoral, clavicular and acromial branches after piercing the clavipectoral fascia. The pectoral branch supplies the sternal pectoral head, while the deltoid branch supplies the clavicular head and the anterior deltoid. The acromial branch supplies the acromioclavicular joint and anastomoses with the suprascapular and posterior circumflex humeral branches. The clavicular branch finally supplies the medial clavicle and sternoclavicular joint. The lateral pectoral artery stems from the axillary artery with variable origins described in the literature. The artery supplies the serratus anterior and pectoralis minor. Distally to the pectoralis minor, the subscapular artery arises and supplies the subscapularis muscle. It also gives off the circumflex scapulae which courses through the triangular space between the teres major, minor and long head of biceps to supply the infraspinatus muscle. The subscapular artery terminates as the thoracodorsal branch alongside the thoracodorsal nerve, supplying the teres major and latissimus dorsi. The next branch of the axillary artery is the posterior circumflex humeral artery. This artery passes through the quadrilateral space alongside the axillary nerve and supplies the middle and posterior deltoid. The smaller anterior circumflex humeral artery opposite from it, travels at the inferior border of the tendinous subscapularis insertion and its anterolateral ascending branch supplies the majority of the humeral head. Multiple anastomoses exist between the various branches (Poldoja et al., 2017).

1.5 Biomechanics

1.5.1 Function

The function of the shoulder complex is to position the hand in space across the largest possible range of motion, exert force at those positions and maintain joint stability throughout the process.

1.5.2 Mobility

1.5.2.1 Scapular Mobility

Shoulder motion is traditionally described as forward flexion (or elevation), retroflexion (or extension), abduction, adduction, internal (medial) and external (lateral) rotation. Clinically these movements are centered around a non-existent humerothoracic joint. In reality, this mobility is the result of motion at both the glenohumeral and scapulothoracic joints. One of the most frequently studied shoulder motions is abduction or elevation in the scapular plane, so-called “scaption”(Moseley et al., 1992). The glenohumeral joint allows for up to 120° of elevation, with the remaining 60° is provided by scapular rotation (Van der Helm & Pronk, 1995). The glenohumeral and scapular contributions follow a pattern termed the “scapulohumeral rhythm”. Some authors have found a constant 2:1 or 3:1 ratio of glenohumeral vs. scapulothoracic motion whereas others have reported more variability (Codman, 1934)(Inman and Abbott, 1944)(Sugamoto et al., 2002). Scapulothoracic rotation increases shoulder range of motion by delaying impingement of the humerus on the coracoacromial arch during abduction, and by extending horizontal flexion and extension via scapular protraction and retraction. Moreover, scapulothoracic motion optimizes the position of the scapula in line with the humeral head which maximizes glenoid support and joint stability, while relieving the suspensory muscles (Culham and Peat, 1993). Scapular mobility is constrained by the shape of the thoracic cage and clavicle, and controlled by the thoracoscapular and humeroscapular musculature (Veeger and Van der Helm, 2007).

1.5.2.2 Glenohumeral mobility

The glenohumeral joint has the largest range of motion of any diarthrodial articulation in the body (An et al., 1991). Such generous mobility is a direct result of the difference in size between the mating articular surfaces of the ball-in-socket joint. The shallow glenoid fossa is approximately three to four times smaller than the humeral head, which allows for a wide range of motion before bony impingement occurs (Fig. 1.7)(Soslowsky et al., 1992). During glenohumeral motion, only a small and constantly changing portion of the humeral head comes into contact with the glenoid, whereas on the glenoid side, the contact area remains relatively constant (Soslowsky et al., 1992). This articular behaviour was mapped and termed the “glenoid track” by Yamamoto and colleagues. The authors demonstrated that during abduction and external rotation, the area of glenohumeral contact covers only 84% of the glenoid width when measured from the articular humeral margin (Yamamoto et al., 2007). A later study under in-vivo conditions corrected this number down to 83%, which is the preferred percentage in current literature (Omori et al., 2014).

The glenohumeral joint generally behaves as a ball-in-socket articulation, and is conceptually considered to have 6 degrees of freedom (3 translational and 3 rotational degrees of freedom). Traditionally, only the rotations are considered clinically significant. Yet, there is some debate concerning whether or not glenohumeral translations parallel to the articular surfaces occur during normal motion. This topic is explored further in the chapter on bone block biomechanics. Several authors have analyzed the cartilaginous surfaces of the glenoid and humeral head and while some studies have indicated that the humeral head can be equated to a sphere (Soslowsky et al., 1992)(Boileau and Walch, 1997), recent detailed computerized surface analyses have indicated that the humeral head is elliptical with the long axis in the superior-inferior direction (Zumstein et al., 2014). These findings corroborate the results of some earlier studies (Iannotti et al., 1992). Importantly, none of these studies take into account the deformability of the cartilage and subchondral bone. During in-vivo motion, glenohumeral compression likely alters the joint surfaces to reduce any radial mismatch and leave a small joint gap for lubrication. A constant fluid film makes almost frictionless motion possible and the deformable labrum around the glenoid is thought to aid in keeping the intra-articular fluid pressure constant and the joint well lubricated (Veeger and Van der Helm, 2007).

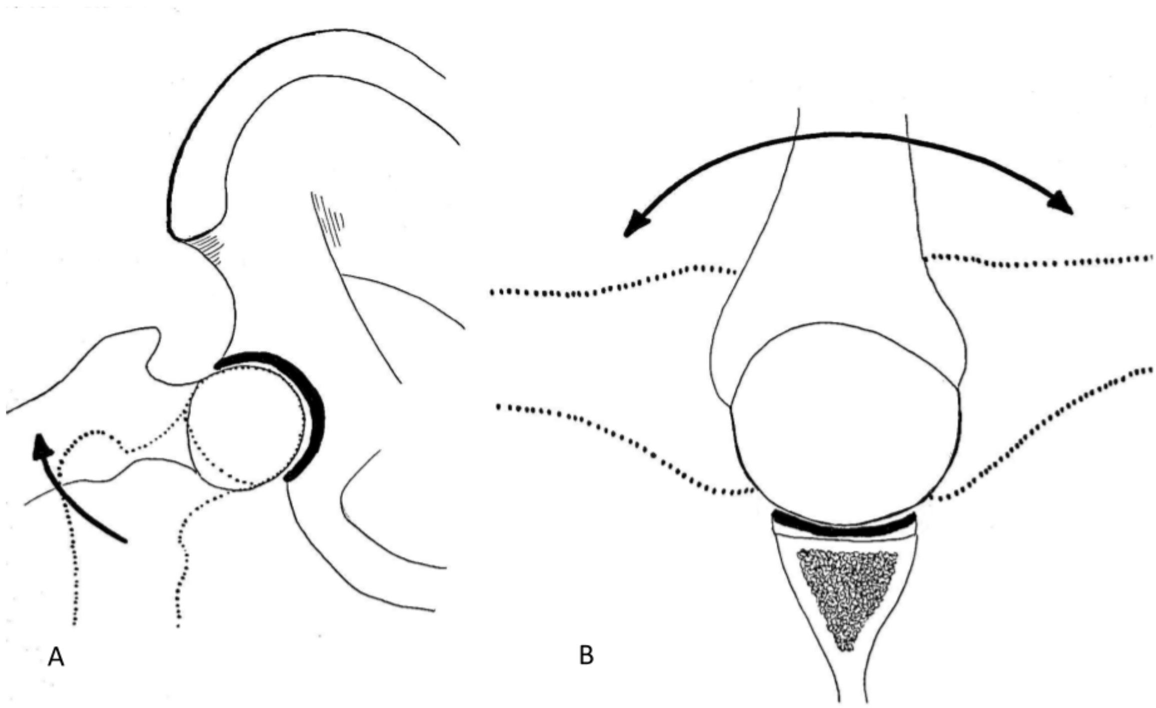

Figure 1.7
Drawing of a hip joint (A) and cross-section of a glenohumeral joint (B). The shallow fossa of the glenoid is about four times smaller than the humeral head. This allows for a much greater impingement-free range of motion compared to joints with more enveloping osseous constraints such as the hip. Adapted from Rockwood and Matsen's The Shoulder, 5th Edition.

1.5.3 Stability

1.5.3.1 Definitions

As mentioned above, the mechanical definition of instability in a clinical musculoskeletal setting is confusing. Similarly, the terms conformity and constraint are often, wrongly, used interchangeably in the literature on glenohumeral instability. Conformity is a measure of similarity in shape, expressed as the mismatch in radius of curvature between the humeral head and glenoid fossa. High conformity equals a small radial mismatch and vice versa. Constraint on the other hand, is defined as the maximum slope at the glenoid rim, which is in turn determined by the angle enclosed by the glenoid, sometimes referred to as "coverage angle" (Anglin et al., 2000). Reducing the humeral head size lowers the translational stiffness, defined as the gradient of subluxation force with respect to humeral head displacement, but does not alter the joint's constraint. Conversely, reducing the glenoid constraint will lower the joint's stability, without necessarily altering the conformity. Another important distinction is made between endrange and midrange motion. When the arm is brought to the limit of motion allowed by the joint, it is defined as endrange. The track made by the arm along the endrange describes a large circle around the shoulder. The area enclosed by this circle is termed the midrange of motion. As discussed below, the difference between midrange and endrange is relevant because the two are believed to be governed by a different set of stabilizing mechanisms. Furthermore, the concept of force couples is introduced. A force couple consists of two parallel forces, equal in magnitude and opposite in sense, which do not share a line of action. The resulting motion is rotation without translation (Nordin, 1989).

1.5.3.2 Bony vs. Soft-tissue Stabilizers

A somewhat artificial distinction is often made between the bony and soft-tissue stabilizing structures of the shoulder. The bony glenoid has a depth of only 2.5 mm in the anteroposterior and 9 mm in the superoinferior direction (Howell and Galinat, 1989). As discussed above, the cartilage distribution may exhibit a central thinning at the “bare spot’ which increases glenohumeral conformity (Soslowsky et al.,1992). Glenoid bony anatomy has only recently been recognized to play an important role in glenohumeral stability. Reduction of glenoid coverage angle by erosion or fracture, severely impacts glenohumeral stability (Itoi et al., 2000)(Montgomery et al., 2005). Moroder et al. demonstrated that inherently flatter glenoids predispose patients to atraumatic instability (Moroder et al., 2015). Additionally, glenoid version has been implicated in shoulder instability. Similarly to posterior instability, where the correlation with glenoid retroversion is more established, recent evidence has come out indicating that greater anterior glenoid anteversion may be correlated to an increased risk of anterior shoulder instability (Hohman and Tetsworth, 2015)(Aygun et al., 2016). For each degree of glenoid anteversion, a reduction in translational force of 6% was observed in one biomechanical study (Eichinger et al., 2016). However, it should be stated that since glenoid version as a 3D concept is only partially explained by 2D measurements, care should be taken to evaluate which measurement technique was used to assess it. A twist in glenoid version has moreover been described when measuring from superior to inferior, making the use of reference planes more complicated (Kwon et al., 2005). Similarly, inferior glenoid inclination, greater scapular internal rotation, decreased upward rotation and decreased dorsal tilt have been linked to anterior shoulder instability (Hohmann and Tetsworth, 2015). The bony scapular spine and acromion effectively prevent posterior and superior migration (Rockwood and Matsen, 2009) and the coracoid process may play a role in limiting anterior humeral translation (O’Brien et al., 1995). This may be why recent modelling experiments have shown a difference in coraco-acromial arch position and coraco-humeral distance between stable and unstable shoulders (Owens et al., 2014)(Jacxsens et al., 2019).

In addition to these bony structures, certain soft-tissue stabilizers are recognized in the shoulder joint. The labrum, a fibrous ring around the glenoid, effectively doubles the glenoid sockets depth and increases the joint’s translational stiffness by 10% (Halder et al., 2001). The labrum also serves as an attachment site for the glenohumeral ligaments and blends into the biceps tendon at the top of the glenoid. The labrum further functions as the rim of a suction cup in the negative intra-articular pressure mechanism. The maintenance of this negative force, which was shown to be 146N on average in cadaveric specimen, depends on the integrity of the articular surface, labrum and capsule (Habermeyer et al., 1992). The glenohumeral capsule is relatively loose and its mechanical role in glenohumeral stability becomes more relevant in the endrange of motion (Apreleva et al., 1998)(Itoi et al., 2000). The coracohumeral ligament and the superior GHL are thought to be inferior stabilizers for the shoulder in the adducted and neutral position (Burkhart and Debski, 2002). The middle GHL is believed to limit external rotation between 0 and 90° of abduction and restrain anterior translation between 0 and 45°. The inferior GHL is considered the most important stabilizer against anteroinferior translation. Especially with the arm in abduction, external rotation and extension (Burkhart and Debski, 2002). It is important to note that the ligaments only exert a stabilizing function after being stretched beyond their resting length. Unlike isometric ligaments, the GHLs have little to no function in the midrange of motion. Up to 5 mm of glenohumeral translation is possible before any serious counteraction by the ligaments is observed (Veeger and Van der Helm, 2007). The rotator interval (RI) lies between the anterior border of the supraspinatus and the superior border of the subscapularis and contains the superior and middle GHL, as well as the coracohumeral ligament. The exact role of the long head of biceps in shoulder stability has been the subject of debate for several decades. It was long believed to be a depressor of the humeral head and tensioner of the capsulolabral complex, yet more recent evidence indicates it may also play a role in the stabilization of the humeral head against anterior displacement, especially in the presence of an inferior GHL injury (Fig. 1.8)(Pagnani et al., 1996)(Abboud and Soslowksy, 2002). Muscle activity is an important part of the soft-tissue stabilization of the joint, as is discussed below. The role of passive muscle tension in shoulder instability is believed to be negligible compared to the dynamic stabilizing function (Motzkin et al., 1994).

1.3.3.3 Static vs. Dynamic Stabilizers

Shoulder stabilizers can be divided in static and dynamic structures. Bony, cartilaginous, capsular and ligamentous structures are considered "static", whereas the surrounding musculature is "dynamic". This distinction is not always clear-cut due to the significant interplay between static and dynamic stabilizers. The static stabilizers function according to the circle concept of capsuloligamentous stability (Abboud and Soslowsky, 2002). In this theory, the static stabilizers form a balanced circle in which excessive translation resulting in damage to the static structures on the side of the translation, will automatically cause injury to the opposite side as well (Fig. 1.8).

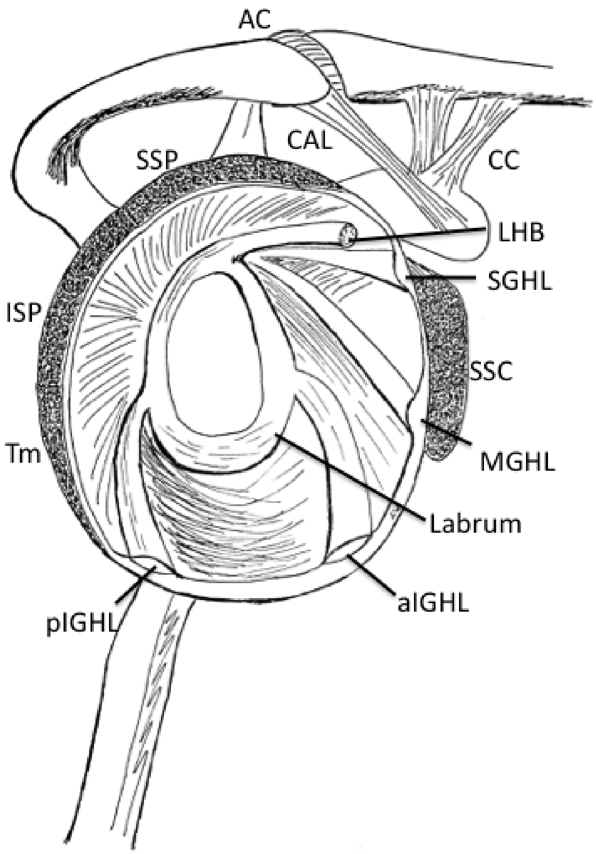

Fig. 1.8
Illustration of the circle concept of the glenohumeral joint. Drawing of a lateral view of a right scapula with the labrum and capsule surrounding the glenoid. The long head of biceps (LHB), the superior glenohumeral ligament (SGHL), the middle glenohumeral ligament (MGHL), and the anterior and posterior bands of the inferior glenohumeral ligament (aIGHL and pIGHL), as well as the supraspinatus (SSP), infraspinatus (ISP), teres minor (Tm) and subscapularis (SSC) muscles are shown. These structures form a circular stabilizer around the glenohumeral joint. Any translation of the humeral head causing damage to the capsuloligamentous structures in the direction of translation, will automatically result in injury to the opposite structures. The acromioclavicular (AC) ligaments, the coracoacromial ligament (CAL) and the coracoclavicular (CC) ligaments are also depicted.

The static structures are also important in the maintenance of articular congruency and constraint necessary for the dynamic stabilizers to function properly. Active or dynamic stability is the result of complex neuromuscular control of the shoulder musculature. On one hand the dynamic muscular stabilizers ensure the scapula is aligned with the humeral head during motion (Rockwood and Matsen, 2009). Much like a seal balancing a ball on his nose, the thoracoscapular muscles position the scapula such that maximal support is given to the humeral head at any given moment. On the other hand, the humeroscapular and thoracohumeral musculature contract in an orchestrated manner to keep the humeral head centralized in the glenoid socket despite the limited static constraints and the large difference in size. Active muscle tension is responsible for the compression of the articular surfaces, a crucial part of the "concavity-compression" mechanism (Lippitt and Matsen, 1993). As the name implies, this mechanism induces stability by compressing the convex humeral head into the concave glenoid socket. Stability is enhanced by increasing the compression force or increasing the socket depth. The more shallow the glenoid socket, the greater the compression force needed to stabilize the joint.

Muscle activity also plays a role by moving the joint into more extreme positions, causing secondary tightening of static stabilizers by wrapping them around the joint, or by creating a muscle barrier effect. Generally speaking, the dynamic stabilizers are coordinated to centralize the joint reaction force into the glenoid socket. When the combined force vector points outside of the glenoid arc, instability will ensue (Fig 1.9)(Lippitt and Matsen, 1993). The rotator cuff muscles are ideally situated to act as force couples around the glenohumeral joint. The intricate interplay between agonist and antagonist muscles with small lever arms provides fine tuning of motion and stability in the glenohumeral joint (Abboud and Soslowsky, 2002). The rotator cuff muscles are also critically important in the compression of the humeral head thanks to their almost concentric lines of pull (Rockwood and Matsen., 2009) Furthermore, the inferior angulation of the subscapularis, infraspinatus and teres minor muscles serves to create a force couple with the deltoid.

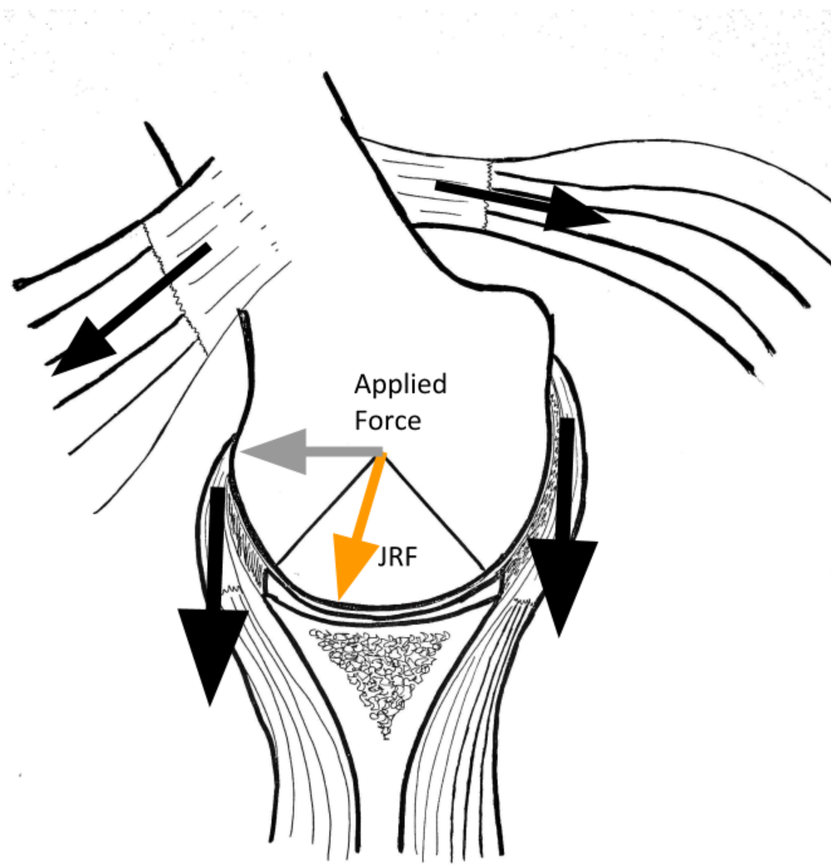

Figure 1.9
Drawing of a cross-sectional view of the glenohumeral joint to illustrate the joint reaction force (JRF). An applied external force (gray arrow) will only result in dislocation if the JRF points outside of the glenoid. This is counteracted by the scapular positioning and by the dynamic concavity compression mechanism. The thoracohumeral, scapulohumeral and

rotator cuff muscles (black arrows) actively compress the humeral head into the glenoid socket, thereby redirecting the JRF (orange arrow) inside the glenoid coverage angle. Adapted from Rockwood and Matsen's The Shoulder, 5th Edition.

1.5.3.4 Endrange vs. Midrange Mechanisms

Midrange stability is ensured by the negative intra-articular pressure (Kumar et al., 1985) and the concavity-compression mechanism (Itoi et al., 1993)(Lippitt and Matsen, 1993). In a relaxed patient with the arm in adduction, a downward pulling force is resisted by the negative pressure. This pressure increases linearly with increased force. The responsiveness of the negative pressure may vary depending on the laxity of the joint. As mentioned above, an intact and congruent articular surface and intact soft tissues are necessary for sustaining negative intra-articular pressure. As soon as muscle contractions occur during motion, the humeral head is effectively pressed into the glenoid socket and stabilized by the concavity-compression mechanism. Due to the shape of the glenoid, translational stiffness in the superior-inferior direction is twice as high as in the anterior-posterior direction. Bony or soft tissue deficiencies on the humeral or glenoid articular side, as well as disruption of the compression mechanism through muscle paralysis or tendon tears, may compromise the concavity-compression mechanism. At the endrange of motion, part of the shoulder capsule and ligaments becomes tight. In maximal abduction, external rotation and horizontal extension for instance, the anterior band of inferior GHL fans out, while the posterior band becomes cordlike and together the bands form a hammock which prevents further translation in the anterior and inferior direction (Fig. 1.5). Insufficiency of the capsule or ligaments due to previous rupture or stretching may cause this mechanism to fail and result in excessive translation of the humeral head as either subluxation or dislocation (Lippitt and Matsen, 1993). A summarizing table of stabilizing mechanisms is given in table 1.3.

Dynamic	**Static**
Rotator Cuff Control	Bony Anatomy
Periscapular Control	Cartilage
Neurology/Proprioception	*Labrum*
Active muscle/tendon barrier	*Glenohumeral ligaments*
Long head of biceps	*Capsule*
	Negative Intra-Articular Pressure
	Passive muscle/tendon barrier

Table 1.3

Summary of stabilizing structures and mechanisms. Dynamic and static stabilizers are listed in order of importance. Midrange stabilizers are greyed, endrange stabilizers are marked in italics.

1.6 Clinical Presentation

1.6.1 History

A careful history should be the basis of any clinical evaluation, likewise in the examination of shoulder instability. General information should be obtained about the patient such as age, profession, sports, hobbies, as well as concomitant medical conditions and injuries. Subsequently, a detailed inventory of the patients complaints should be made. These may include pain, instability, catching, locking, apprehension, stiffness, swelling and deformity. First-time dislocators may recount a single traumatic event, possibly followed by one or more recurrences. Alternatively, patients may emphasize limitations and apprehension due to multiple instability events with only a vague memory of the initial injury. When possible, a detailed description of the trauma mechanism should be recorded, with special attention to the nature of the activity, the direction of applied force during the injury and the perceived direction of instability during the event. Furthermore, attention should be paid to the ability of the patient to self-reduce the shoulder. If the patient underwent closed reduction by a third party, it is of interest to find out which method was used and what the duration of dislocation was before reduction. In cases of recurrent shoulder instability, it is important to determine the amount of energy required to dislocate. Some patients will only recur during high energy sporting or traumatic events, while others may dislocate during normal everyday activities or even during sleep (Gil and Owens, 2017). Patients with hyperlaxity tend to present with vague symptoms of shoulder looseness or slipping during everyday activities. A thorough history should reveal which activities are most problematic to the patient, in order to specify the type and main direction of instability (Johnson et al., 2010). Apprehension in a specific position is more common in traumatic unilateral instability, whereas pain is more often associated with instability due to ligamentous hyperlaxity (Haley, 2017). When a volitional component is suspected, a more in-depth psychological evaluation should be performed (Johnson et al., 2010).

1.6.2 Clinical Exam

A classic clinical shoulder examination includes inspection, palpation, as well as motion and strength evaluation. Inspection should be performed with attention to deformity, muscle atrophy and scar formation. Scars may reveal previous surgical procedures and the presence of widened scars may suggest an underlying collagen disorder. Palpation is performed to detect deformity, tenderness or crepitus. It is important to perform a sensory exam of the upper limb, with specific attention to the lateral upper arm area, and to palpate for the presence of active deltoid contraction. Palpation of distal arterial pulse and capillary refill may be relevant in cases of suspected vascular injury. Formal testing of passive and active range of motion is important in the preclusion of rotator cuff injury and may reveal apprehension when present. It is also crucial in the detection of posttraumatic frozen shoulder and plays a role in the assessment of hyperlaxity as discussed further on. Strength testing should be performed with special focus on the deltoid and teres minor for the detection of axillary lesions, as well as separate testing of the rotator cuff muscles for the detection of acute tendon tears (Haley, 2017).

Specialized tests are included in the exam of the unstable shoulder. The load-and-shift test, first reported by Hawkins (Hawkins et al., 1988), involves the examiner placing one hand over the glenohumeral joint line while applying concentric pressure and anterior translation to the humeral head with the other hand. This test assesses the amount of laxity or translation in the joint and has shown optimal reliability (Tzannes et al., 2004). Similarly, the drawer test involves the examiner cradling the supine patients forearm in his or her axilla while applying anterior or posterior translation to the upper arm with one hand and assessing the translation and stabilizing the scapula simultaneously with the other (Gerber and Ganz, 1984). The sulcus test involves the observance for a depression between the acromion and the humeral head when applying longitudinal traction. A positive test indicates a dysfunction in the CHL, superior GHL or Rotator Interval (RI), especially when persisting throughout external rotation (Neer, 1985). The gradation of severity during these tests is difficult due to the inaccuracy of estimated millimeters or percentages. Therefore, translation is typically described in reference to the glenoid rim. Patients may be lax (excessive displacement), subluxating (displacement of the head over the glenoid rim) or dislocating (displacement over the glenoid rim to a locked position) according to this system (Altchek et al., 1991).

Provocation tests include a series of manoeuvres intended to destabilize the joint and as such reveal the symptoms of instability (Fig. 1.10). Although the tests are primarily suited to detect capsuloligamentous stability, they automatically challenge the dynamic stabilizers as well. The apprehension manoeuvre is performed by abducting and externally rotating the seated or supine patients arm. Pain or apprehension during this test may be regarded as a positive result. The apprehension test is then repeated while the examiner places a hand over the anterior humeral head and exerts a posterior counterforce. A reduction in apprehension, and to a lesser degree pain, is indicative of anterior instability. Finally, a surprise release of the relocation pressure can be performed to assess the return of apprehension. This series of tests has shown high sensitivity, specificity and predictive value for symptomatic anterior shoulder instability (Lo et al., 2004). Lafosse recently described a new test in which asymmetry during hyperextension and internal rotation of the shoulder (HERI test) was shown to be indicative of an injury to the inferior GHL (Lafosse et al., 2016). Additionally, the Beighton score can be administered to grade general hyperlaxity. This score evaluates laxity in hands (four points), knees (2 points), elbows (2 points) and spine (1 point). A patient scoring higher than 4 points is considered hyperlax (Johnson et al., 2010). The Gagey test is more specifically geared towards the assessment of shoulder hyperlaxity. Hyperabduction of the shoulder to 105° is indicative of laxity or injury of the inferior GHL (Gagey and Gagey., 2001).

Figure 1.10
Drawing of the apprehension-relocation test. The examiners right hand is externally rotating the supine patients left shoulder in abduction. In the case of a positive apprehension test, the examiner applies downward pressure on the humeral head to test for a positive relocation sign. A final test in the provocative test series is to suddenly release the relocation pressure and observe for the return of apprehension or pain.

Examination of the shoulder under anesthesia is considered an important step in the clinical assessment of the unstable shoulder. Most of the translational tests mentioned above can only be performed correctly when the patient is completely relaxed. Hence a repetition of these tests and range of motion under anesthesia is extremely informative. Both shoulders should be tested for degree and direction of instability in various positions of abduction and rotation (Cofield and Irving, 1987).

1.7 Imaging

1.7.1 Radiography

Initial imaging of shoulder instability is performed by traditional radiography. Classic anteroposterior and “Y” scapular views of the shoulder provide an overview of joint alignment, bony anatomy and osseous injuries. Bony lesions are frequent after anterior dislocation. Injuries to the anterior glenoid rim are termed “bony Bankart” lesions, while impression fractures of the humeral head are known as “Hill-Sachs” lesions in reference to the two American radiologists who were amongst the first to describe the lesions and mechanism of injury (Somford et al., 2017). Additional information is gathered by obtaining an axillary view of the joint if the patient is able to abduct the arm sufficiently. Specialized views such as the Stryker Notch, West Point and Velpeau views have largely fallen out of favour due to the availability and accuracy of more advanced imaging techniques (Kompel et al., 2017). One exception is the Bernageau profile view, in which the x-ray beam is aimed from a 30° angle cranially in alignment with the scapula while the patient fully abducts the arm. This method may constitute a cost-effective alternative to computed tomography in the detection of anterior glenoid bone loss (Murachovsky et al., 2012).

1.7.2 Computed Tomography

Computed Tomography (CT) has become the imaging workhorse in the quantification of bony lesions in anterior shoulder instability. CT provides fast and detailed bony imaging, yet exposes the patient to the radiation equivalent of one transatlantic flight (Iordache et al., 2017). Several techniques have been described to calculate the extent of bone loss at the glenoid. Two-dimensional (2D) and three-dimensional (3D) reconstructions of the glenoid allow precise estimation of bone loss by employing the glenoid width or circle methods. The glenoid width method, introduced by Griffith (Griffith et al., 2003), is based on a comparison of the maximum glenoid width of the injured side to the contralateral healthy side. This relatively simple technique has been found to be reliable and accurate (Griffith et al., 2008). Alternatively, the authors suggested normalizing the glenoid width by comparing the width-to-length ratio of the healthy and injured sides (Griffith et al., 2003). The circle method (or “Pico” method) involves using the best fit circle to the inferior glenoid and measuring the defect surface area as a percentage of the entire best fit circle (Baudi et al., 2005) (Fig 1.11). The inferior glenoid circle has been proven to be the most reliable feature of glenoid anatomy. As originally reported by De Wilde et al., the inferior quadrants of the glenoid, which originate from a separate ossification center, exhibit significantly less anatomical variation than the superior quadrants (De Wilde et al., 2003). Techniques based on inferior glenoid measurements have been shown to be accurate and reliable in both 3D and 2D CT (Magarelli, 2009). Others have proposed using the presumed best fit circle by fitting a circle to the ipsilateral posterior uninjured glenoid rim. This modification has shown acceptable inter and intra-observer reliability and avoids the need for contralateral shoulder imaging. This can be of great importance in cases with bilateral glenoid injury (Sugaya, 2014). A simple and validated measurement reported by Chuang et al., closely resembles the method of Griffith et al., by simply calculating the ratio of the injured glenoids width to the uninjured glenoids inferior circle diameter. The authors found a ratio of 0.75 predictive in the need for bone grafting (Chuang et al., 2008). Barcilon et al., similarly used this technique in a unilateral manner with good results (Barcilon et al., 2008). Alternatively, the Gerber index published by Nyfeller and Gerber calculates the ratio between the defect length and the maximal glenoid width. This index has been shown to be biomechanically relevant but has infrequently been used in the literature (Gerber and Nyfeller, 2002)(Sommaire et al., 2012). It is important not the compare percentages of Gerber index reports to glenoid width ratios. On the humeral side, no single technique has been universally accepted in the calculation of bone loss. Several methods have been reported, yet the measurement of width and depth on axial slices, and the loss of articular arc seem to be the most reliable and accurate (Provencher et al., 2012). Moreover, functional and dynamic techniques such as the “glenoid track” concept have gained prominence over descriptive measurements in recent years (Yamamoto et al., 2007). In regards to soft-tissue lesions, CT and specifically CT arthrography, which involves the intra-articular injection of radio-opaque dye, has proven valuable in the detection of capsuloligamentous and cartilaginous lesions. However, magnetic resonance imaging is still the preferred technique for these injuries (Acid et al., 2012). Conversely, CT imaging has recently regained importance in the assessment of glenohumeral bony morphology and the quantification of glenoid and humeral version and tilt.

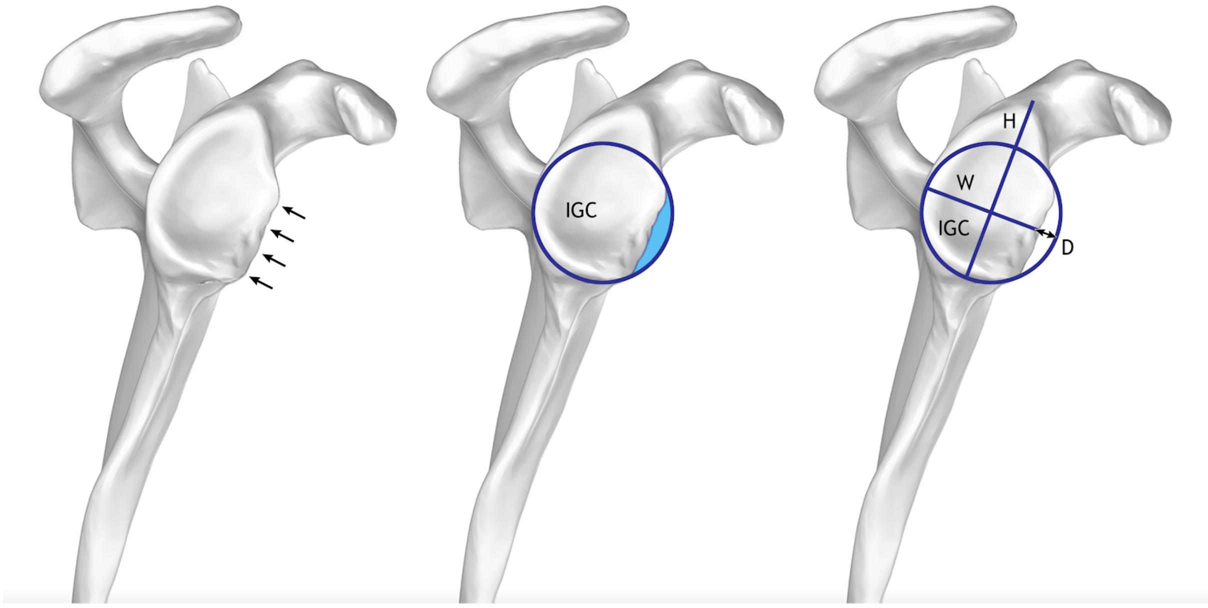

Fig. 1.11
Illustrations depicting the lateral view of a right scapula with substantial anterior glenoid bone loss (arrows left image), the best-fitting inferior glenoid circle (IGC), and the defect surface area (light blue, middle image). The linear methods for comparing the width of the defect (D) and the maximal IGC width (W) is shown in the right image. Independently of the inferior circle, the Griffith method of maximum width can be measured perpendicular to the long axis of the glenoid. Glenoid height (H) can be used for the normalization of the glenoid width in comparison with the contralateral healthy shoulder, using the width-length ratio. The Glenoid index method compares the width (W) of the injured side to the diameter of the ICG of

uninjured side. (Reproduced with permission from Willemot, L. B., Elhassan, B. T., & Verborgt, O. (2018). Bony Reconstruction of the Anterior Glenoid Rim, *26*(10), e207-e218. https://doi.org/10.5435/jaaos-d-16-00649.)

1.7.3 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) has been heralded as the ultimate diagnostic tool in shoulder instability. MRI provides the required soft-tissue contrast needed for the diagnosis of capsulolabral injuries without the risks of radiation. Capsulolabral avulsions of the anterior glenoid, termed Bankart injuries, are typically found after one or more episodes of anterior traumatic instability. Several variants have been described, such as the bony Bankart lesion in which a fragment of bone is fractured or avulsed from the glenoid, the Perthes lesion in which the anterior glenoid periosteum is stripped but remains in-situ, the anterior labroligamentous periosteal sleeve avulsion (ALPSA) in which the labrum is healed in a medialized position on the glenoid neck, the glenoid labral articular disruption (GLAD) in which a fragment of articular cartilage is attached to the avulsed labrum and the humeral avulsion of GHL (HAGL) in which the inferior GHL is avulsed from the humeral side and not the glenoid (Fig. 1.12)(Woertler and Waldt, 2006). These subtle findings, as well as other concomitant injuries such as rotator cuff tears or undisplaced fractures are more conspicuous on MRI than other modalities. The addition of intra-articular gadolinium contrast further increases the sensitivity and specificity of the exam, although developments in magnet strengths, shoulder coils and imaging sequences have increased the capabilities of unenhanced MRI (Magee, 2009)(Jonas et al., 2012)(Bencardino et al., 2013). In regards to bony lesions, MRI is currently not considered as sensitive as CT, yet has shown to be accurate and reliable in the detection and quantification of glenohumeral bone loss. Dedicated MRI sequences and post-imaging modifications may optimize the use of MRI for the assessment of bony injuries in the future (Gyftopoulos et al., 2012)(Lee et al., 2013)(Sugaya et al., 2014)(Breighner et al., 2017). MRI contra-indications include claustrophobia, electromagnetic implants and other metallic implants.

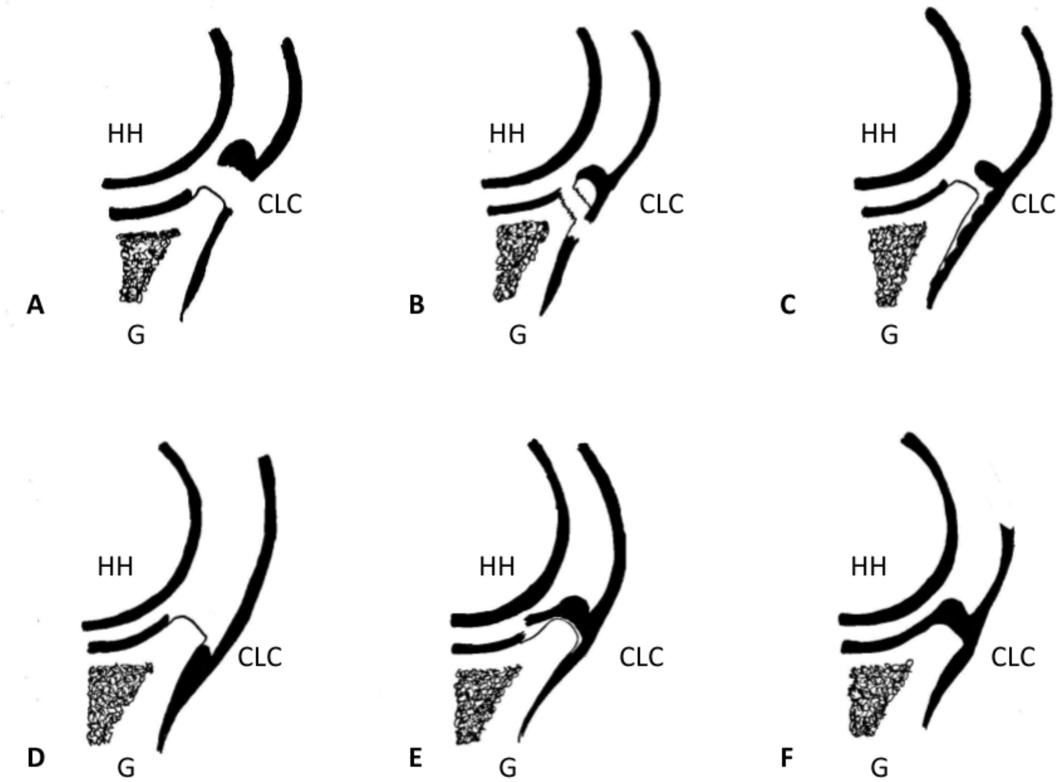

Fig. 1.12
Drawing of Bankart lesion variants. Cross-sectional image of the glenoid (G), humeral head (HH) and capsulolabral complex (CLC). Panel A; classic Bankart lesion, panel B; bony Bankart lesion, panel C; Perthes lesion, panel D; ALPSA lesion, panel E; GLAD lesion, panel F; HAGL lesion. Adapted from Woertler, K., & Waldt, S. (2006). MR imaging in sports-related glenohumeral instability, *16*(12), 2622-2636.)

1.8 Surgical Exploration

Surgical exploration is often regarded as the gold standard by which clinical diagnostic tests and imaging modalities are gauged. Exploration is usually performed via arthroscopy and allows for direct visualization and manipulation of the tissues. Despite the obvious advantages of real-time surgical inspection and the possibility of immediate intervention, excessive trust in the surgical explorative method may result in judgement errors on the part of the arthroscopist. However, since arthroscopy is frequently used as the ultimate step in diagnostic evaluation and findings are heavily dependent on the skills and thoroughness of the surgeon, such errors are difficult to prove in the literature. Nevertheless, a significant body of work exists when it comes to the comparison of surgery and imaging methods for the evaluation of anterior bone loss. Burkart and colleagues described the bare spot method as a valid technique for the intra-operative assessment of anterior glenoid defect size. As shown in figure 1.13, a hooked surgical instrument with linear marks is used to gage the distance from the anterior glenoid rim to the bare spot, and from the bare spot to the posterior glenoid edge (Burkart et al., 2002). However, subsequent publications have made it abundantly clear that arthroscopy tends to overestimate glenoid bone loss (Bakshi et al., 2015). This may be explained by the coarseness of the measuring device, the inconsistencies in presence and location of the bare spot, or both (Kralinger et al., 2006)(Myatake et al., 2014).

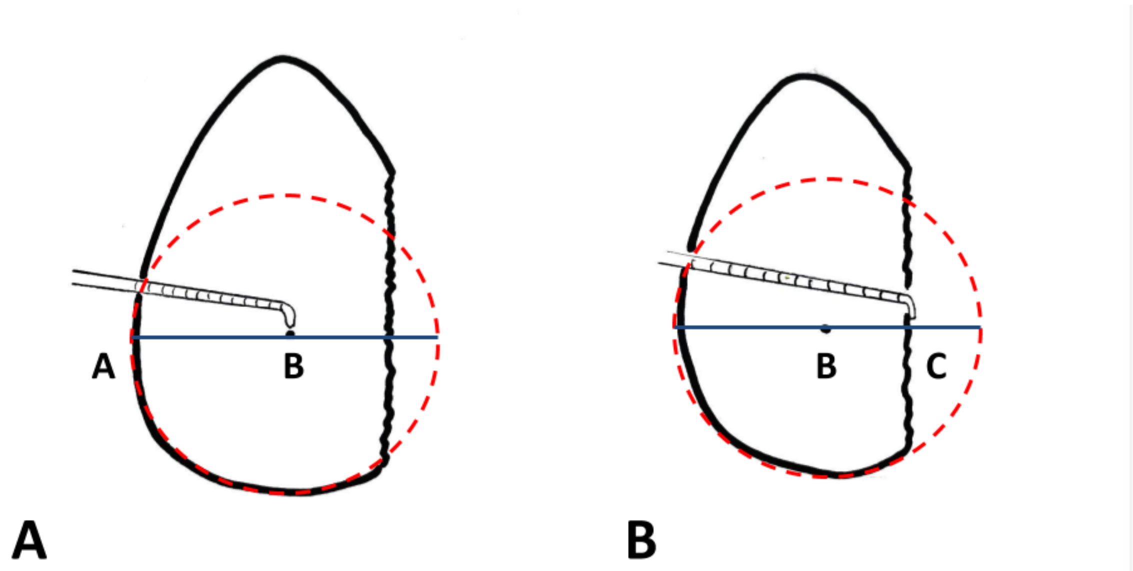

Figure 1.13
The bare spot method involves measuring the distance between the intact posterior rim (A) and the glenoid bare spot (B) and the distance between the injured anterior rim (C) and the bare spot, assuming that the bare spot is present and located centrally in the inferior glenoid circle. Using the graded instrument the percentage of bone loss is calculated by subtracting BC from AB and dividing it by two times AB. Adapted from Burkhart, et al., (2002). Quantifying glenoid bone loss arthroscopically in shoulder instability. *Arthroscopy*, *18*(5), 488–491. https://doi.org/10.1053/jars.2002.32212

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Chapter 2: Anterior Glenoid Bone Grafting

"Isn't it a bit unnerving that doctors call what they do "practice"?"

George Carlin

Overview

This chapter includes an overview of the distinct patho-anatomical lesions associated with recurrent shoulder instability, conservative and surgical treatment options and in-depth description of historical and current bone grafting procedures in shoulder instability.

2.1 Patho-anatomy

2.1.1 Introduction

Significant injury to the humeral head, glenoid, articular cartilage, capsule, glenohumeral ligaments, labrum, rotator cuff tendons and biceps tendon may be present after primary dislocation or subluxation. The prevalence and severity of such injuries is known to increase with repeated instability events (Habermeyer et al., 1999)(Yiannakopoulos et al., 2007).

2.1.2 Mechanism of Dislocation

In order to understand the patho-anatomical lesions of the shoulder, the mechanisms of shoulder dislocation should be clarified. It is widely believed that shoulder dislocation takes place during shoulder abduction, extension and external rotation. However, video analysis of anterior shoulder dislocations during rugby matches, has shown more variability in trauma mechanisms. Crichton and colleagues grouped the dislocation mechanisms into three different types. The first type tends to arise after a fall on a hyperflexed outstretched arm, the second type occurs during tackling manoeuvres, and the third type happens during landing or by contact with another player. The first type is the result of the ground reaction force on the outstretched limb, which is transferred to the shoulder and associated with labral injury, rotator cuff tears and dislocation. The second type is due to an extension force on the tackling players abducted arm, creating a large moment on the shoulder and resulting in labral injury and dislocation. The third type is caused by a direct medial force on the posterolateral shoulder associated with scapular fracture, AC joint injury and dislocation (Crichton et al., 2012). Others have additionally ascribed shoulder dislocation to falling backwards on an outstretched arm (Sheehan et al., 2013). Much remains unknown about instability mechanics due to the difficulties of safely recreating the energy and speed of an acute dislocation in the laboratory environment. The apprehension position is widely believed to be provocative, despite several studies disproving the phenomenon of excessive anterior humeral translation during this manoeuvre (Tanaka et al., 2012)(Kim et al., 2017). The excessive translation and rotation of the humeral head during dislocation results in injury to the shoulder structures via traction and shearing forces. Traction on the anterior capsule can cause a variety of injuries to the anterior capsulolabroligamentous complex (CLC) structures as discussed below. Alternatively, the same rotational forces can cause avulsion fractures of the anterior glenoid rim. Shoulder dislocation associated with a more significant axial impact force can result in fracture of the glenoid, usually creating a larger glenoid fragment compared to avulsion mechanisms (Fig. 21.1)(Patel et al., 2014). Impression fractures of the anterior glenoid, sometimes referred to as “erosion fractures” are another cause of glenoid bone loss, especially in recurrent dislocators (Sugaya et al, 2004). However, anterior glenoid bone loss may also be the result of resorption of bone fragments after fracture. Severe resorption of glenoid rim fractures is typically seen within the first year after trauma (Nakagawa, 2013). After dislocation, the soft humeral head is impaled on the hard anterior glenoid rim by secondary muscle contraction. Impression fractures of the posterosuperior humeral head are termed “Hill-Sachs” lesions after two radiologists who were amongst the first authors to describe the findings (Hill and Sachs, 1940).

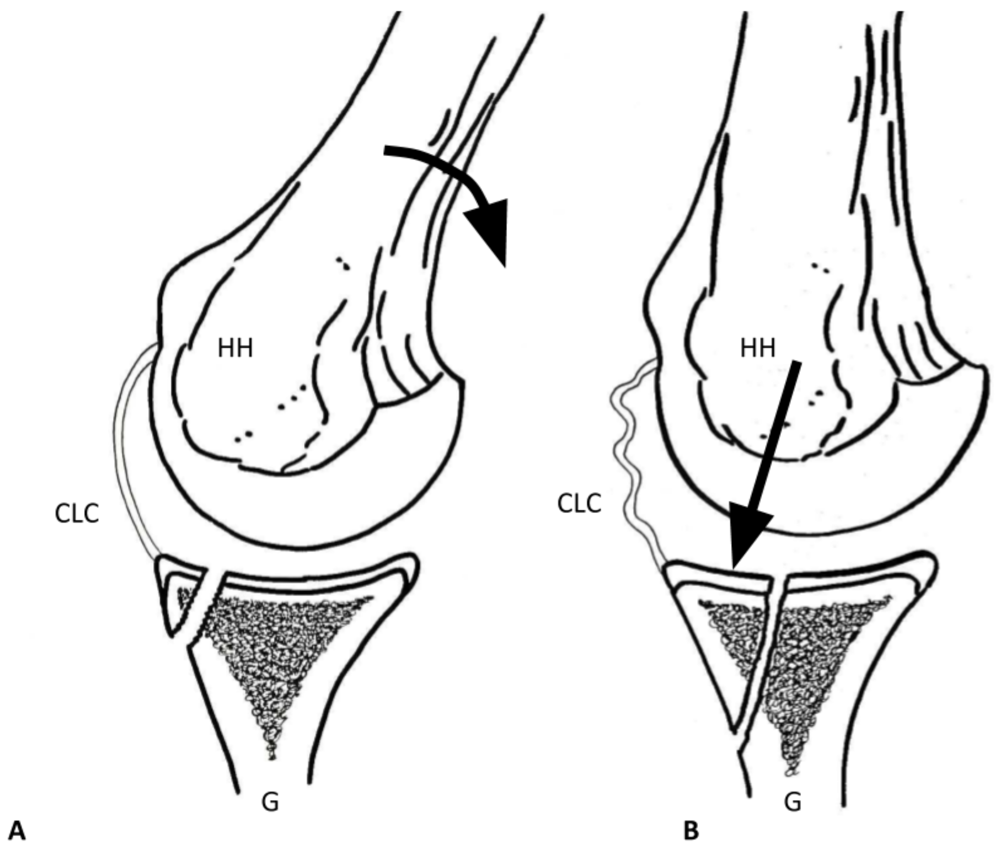


Figure 2.1
Diagram of glenohumeral interaction during the creation of a glenoid rim fragment. Panel A shows the avulsion of a small glenoid (G) rim fragment by the capsulolabral complex (CLC) as a result of excessive rotation. Panel B shows the fracturing of a larger glenoid fragment as result of a medially directed axial impact force of the humeral head (HH) on the glenoid.

2.1.2 Soft-Tissue Lesions

The essential soft-tissue lesion of anterior traumatic shoulder instability is believed to be the so-called Bankart-lesion. The lesion described by Bankart in 1923 specifically refers to a detachment of the CLC from the anterior glenoid rim (Fig. 2.2). This detachment results from traction placed on the capsule and labrum by the translating humeral head. The eponym has become a collective term for various capsulolabral injuries related to shoulder instability. Perthes, described a very similar lesion some years before Bankart, yet his name has become associated with a variant of the lesion in which the CLC is torn from the glenoid in continuity with the stripped periosteum of the anterior glenoid (Fig. 2.2)(Perthes, 1906). Classic Bankart and Perthes lesions are believed to constitute 80% of CLC injuries in anterior shoulder instability (Warner and Beim, 1997). Healing of a Perthes lesion in a medialized position on the glenoid neck is called an anterior labroligamentous periosteal sleeve avulsion (ALPSA). ALPSA lesions have been known for a long time, but have only gained recognition as a distinct category of labral lesion since their description by Neviaser in 1993. (Neviaser, 1993). The pathogenesis is disputed, yet the lesions are associated with more significant concomitant injury (Lee et al., 2011). The correlation of ALPSA lesions with more significant bony injuries may explain why this lesion is associated with higher recurrence rates.

Midsubstance capsular tears have also been observed in primary and recurrent instability cases (Fig. 2.2). Such lesions can be hard to recognize and are often described as “elongated” or “stretched” capsule after healing. Midsubstance tears are frequently associated with more classical CLC injuries, yet isolated complete tears have been found to be the sole responsible instability lesion in 4% of cases undergoing arthroscopic repair (Mizuno et al., 2005). Another infrequent type of anterior capsular injury is the humeral avulsion of the glenohumeral ligaments (HAGL). This type of lesions is observed in 9% of cases, and is frequently missed during arthroscopy. Several subtypes have been defined by Bui-Mansfield, distinguishing anterior and posterior types, as well as bony HAGLs and floating HAGLs in which a combined Bankart lesion and HAGL are present (Bui-Mansfield et al., 2007). Equally uncommon are the occurrence of anterior labral tears extending into the biceps anchor or even to the posterior labrum. Such superior labral avulsion from anterior to posterior (SLAP) and pan-labral tears, can be found after either primary or recurrent traumatic instability. They are the result of excessive anterior humeral translation causing direct injury to the anterior stabilizing structures and indirect injury to the posterior structures, as explained by the circle concept in Chapter 1. These extensive lesions present a technical challenge to the treating surgeon and are often complicated by persistent symptoms of pain and stiffness (Van Blarcum, 2017). As mentioned earlier, shoulder instability may be accompanied by rotator cuff injury. However, the description and treatment or concomitant rotator cuff tears is beyond the scope of this thesis.

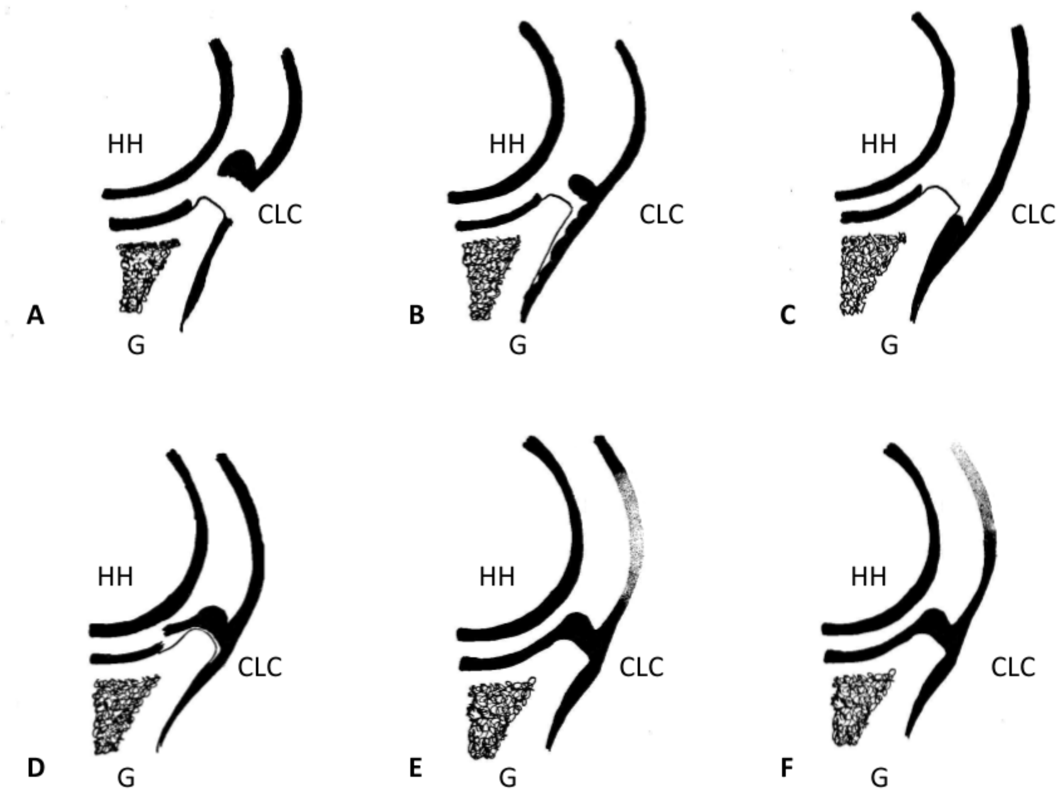


Figure 2.2
Drawing of Bankart lesion variants. Cross-sectional image of the glenoid (G), humeral head (HH) and capsulolabral complex (CLC). Panel A; classic Bankart lesion, panel B; Perthes lesion, panel C; ALPSA lesion, panel D; GLAD lesion, panel E; Midsubstance tear, panel F; HAGL lesion. Adapted from Woertler, K., & Waldt, S. (2006). MR imaging in sports-related glenohumeral instability, *16*(12), 2622-2636.)

2.1.3 Bony Lesions

2.1.3.1 Humeral Bone loss

The bony lesions of the humeral head present after shoulder dislocation bear the eponym “Hill-Sachs” after the two radiologists who were amongst the first to describe the mechanism by which the soft humeral head is compressed against the anterior glenoid rim during dislocation (Hill and Sachs, 1940). Hill-Sachs lesions have been found in 67% of primary dislocations and are almost ubiquitous in recurrent dislocators (Rowe et al., 1984)(Widjaja et al., 2006)(Yiannakopoulos et al., 2007)(Spatschil et al., 2006). There is some debate as to whether the lesions are created by a compressive force of the glenoid rim on the posterosuperior humeral head during dislocation (Provencher et al., 2012), or by the secondary muscle spasm after dislocation impressing the glenoid rim into the humeral head. Several classifications have been proposed to grade the severity of these lesions. The simplest of these is the Calandra classification which divides lesions as outside of, overlapping with, or inside of the humeral articular cartilage (Calandra et al., 1989). However, more comprehensive descriptions are required to assess the risk a lesion poses to recurrence.

Much research has been dedicated to the measurement of Hill-Sachs lesions’ size and orientation. When analyzing the lesions on axial images, with the biceps groove as reference point on a right shoulder (12 o’clock), the average Hill-Sachs lesion is found at 07:58, and between 0 and 24 mm from the top of the humeral head. The inferior part of the lesion sometimes overlaps with the bare area (Saito et al., 2009). In a biomechanical study, Kaar et al. reported a significant decrease in glenohumeral translational force after the creation of a Hill-Sachs lesion greater than 62.5% of the radius of the humeral head (Kaar et al., 2010). Similar cadaveric research by Sekiya found significant instability after the creation of a 37.5% defect (Sekiya et al., 2009). Clinically, a clear association between increasing size of a Hill-Sachs lesion and recurrent dislocation has been reported, yet a fixed critical threshold value has not been agreed upon (Balg and Boileau, 2007)(Burkhart and de Beer, 2000)(Lee et al., 2018).

A more functional determination of risk is to assess whether or not the bony lesion encroaches on the anterior rim during rotation. This process of destabilization during contact between the Hill-Sachs lesion and the glenoid was originally termed “engagement” by Burkhart and de Beer. Depending on the lesions size, location and orientation this can happen at various degrees of abduction, elevation and external rotation. The authors proposed intraoperative dynamic examination to allow visualization of engagement of the lesion. Engaging lesions were believed to require bony augmentative surgery rather than capsular repair, due to their highly destabilizing effect on glenohumeral motion (Burkhart and de Beer, 2000). Some have criticized the usefulness of this distinction, claiming that any Hill-Sachs lesion can be made to engage with forceful external rotation. Itoi later remarked that dynamic examination is more informative when performed after capsular repair, in order to assess engagement during the restored “normal” range of motion. However, this is a moot point, since many surgeons are hesitant to stress a freshly repaired anterior capsule and labrum (Itoi et al., 2017). Alternatively, a virtual assessment can be made by evaluating the glenoid track. This concept, first described by Yamamoto in 2007, tracks the contact area between glenoid and humeral head during abduction, external rotation and extension along the endrange of motion (Fig 2.5). The glenoid track has been shown to extend medially from the rotator cuff footprint to a distance of 83-84% of the glenoid width. When the Hill-Sachs lesion is contained within the glenoid track, enough bony stability is present and the lesion is termed “on-track”. However, when the lesion is large enough, or medial enough to override the medial border of the glenoid track, the lesion is called “off-track”, and more overt instability is to be expected due to the lack of bony support (Di Giacomo et al., 2014). Moreover, additional bone loss on the glenoid side further disturbs the mechanics of the glenohumeral joint as discussed below. This concept has greatly helped in the understanding of recurrent glenohumeral instability (Shaha et al., 2016).

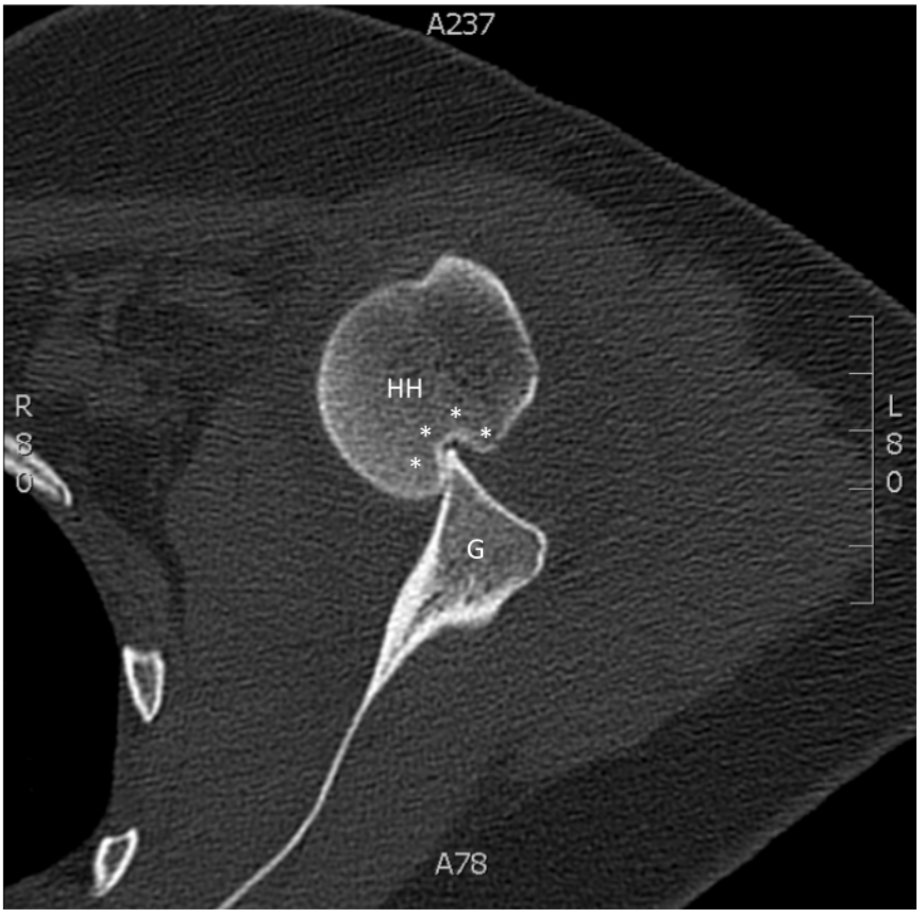


Figure 2.3
CT axial image of an anteriorly dislocated humeral head. The sharp anterior glenoid (G) rim has created a Hill-Sachs (asterisks) lesion by compressing the soft cancellous bone of the humeral head (HH).

2.1.3.2 Glenoid Bone loss

Bony lesions of the anterior glenoid are typically grouped under the eponym “bony Bankart” lesions. As mentioned above, these include avulsion fractures of the CLC, glenoid rim fractures, impression fractures and erosive or attritional anterior glenoid bone loss. CT based prevalence studies have shown bony glenoid lesions in 41% of first-time, and 80% of recurrent dislocators. The most frequent pattern observed is attritional bone loss, with fractures occurring only in 21% of patients (Griffith et al., 2008). Glenoid bone loss was long believed to be located in the anteroinferior quadrant of the glenoid (Itoi et al., 2003). Until Saito and colleagues definitively demonstrated that if the glenoid is likened to a clock face with the superior glenoid tubercle at 12 o’clock, anterior glenoid bone loss occurs at the 3 o’clock position, parallel to the superoinferior glenoid axis (Saito et al., 2005). The confusion is partly explained by the natural anterior tilt of the scapula on the thorax, and the uncertainty about the actual direction of the translating humeral head (Itoi, 2017)(Fig. 2.4). Importantly, the location of anterior glenoid bone loss in relation to the inferior glenoid circle seems to be more relevant than its relationship to the overall glenoid shape (De Wilde et al., 2004).

Glenoid bone loss was originally classified according to the type of bone lesion by Bigliani. Four types were identified; type I lesions presenting as displaced bony avulsions with an attached capsule, type II as medially displaced fragment malunions, type III as erosions of the glenoid rim of less than 25% (IIIA) or more than 25% (IIIB). Anterior glenoid erosions of more than 25% with an elongation inferior GHL were classified as type IV (Bigliani et al., 1998). Biomechanically, Yamamoto and colleagues reported a threshold level of bone loss of 25% of glenoid width. Bone loss of this magnitude resulted in significant loss of translational force during compressive testing on cadaveric joints. Anterior glenoid bone loss effectively leads to a net loss of articular constraint due to the diminished glenoid coverage angle (Yamamoto et al., 2010). This, in turn, impedes the correct functioning of the concavity compression mechanism. The flatter glenoid requires more active stabilization by the cuff musculature to accurately centralize the humeral head in the socket during the midrange of motion. Biomechanical experiments have shown that stability in the endrange of motion is not affected by glenoid bone loss in the presence of functioning capsuloligamentous structures (Itoi et al., 2000). Similarly to the quantification of humeral bone lesions, cut-off levels of significant glenoid bone loss are somewhat artificial. A recent cadaveric study by Shin and colleagues recommended restoring glenoid bone loss of more than 15% due to restrictions of humeral rotation, humeral head centering and loss of glenohumeral stability (Shin et al., 2016). This recommendation is lower than traditionally accepted 25% (Yamamoto et al., 2010), and closer to the reported clinically relevant levels of 13.5% and 17.3% (Shaha et al., 2015)(Shin et al., 2017).

Dynamic investigations such as the glenoid track concept have shed more light on the role of anterior rim defects. Bakshi and colleagues demonstrated the inherent inaccuracy of linear measurements in the determination of glenoid bone loss. The authors confirmed the theoretical suspicion that linear measurements, based on geometric assumptions, overestimate the actual amount of bone loss, as measured by total loss of glenoid surface area (Bakshi et al., 2018). In addition to these findings, it has been shown that the glenoid morphology of unstable shoulders is inherently different than that of stable joints, with unstable glenoids exhibiting a distinctly flatter articular surface (Moroder et al., 2015). Moroder et al., also proved the non-linear biomechanical effect of anterior glenoid bone loss on shoulder stability in a mathematical model. Glenoid rim loss caused a significantly greater loss of translational resistance than a similar area of bone loss beyond the rim. This effect was even more pronounced in more concave glenoids (Moroder et al., 2019). The mere analysis of glenoid bone loss, in addition to the ubiquitous measurement errors, does not take into account the subtle specifics of glenoid morphology such as concavity and version. These factors will require further quantification in the appreciation of the role of glenoid bone loss in anterior shoulder instability (Griffin et al., 2018).

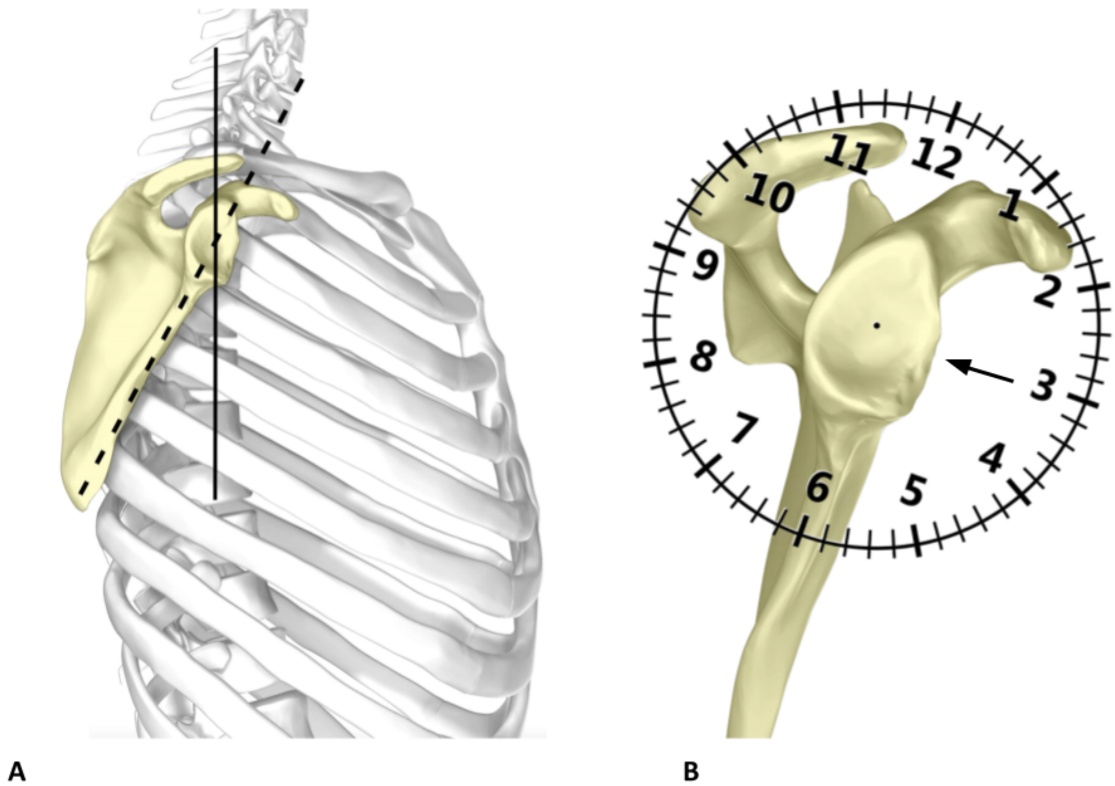


Figure 2.4
Lateral view of a right scapula and thorax (A). Vertical axis is shown as a full line, compared to the dotted line of the scapular tilt axis. En face view of a right glenoid with superimposed clock face demonstrates anterior glenoid bone loss at the 3 o'clock position (B).

2.1.3.2 Bipolar lesions

The simultaneous presentation of a bony Bankart and a Hill-Sachs lesion is often referred to as "bipolar" bone loss. In light of the prevalence of glenoid and humeral bone loss separately, it should be unsurprising that the combination of both lesions is relatively frequent. The prevalence of bipolar bone loss is believed to be somewhere between 33% and 70% in primary instabilities, and 68% and 84% in recurrent cases (Widjaja et al., 2006)(Griffith et al., 2008)(Nakagawa et al., 2015). In a population of male athletes with traumatic anterior shoulder instability, Nakagawa found an overall prevalence of 50.6% (Nakagawa et al., 2018). Finite element analysis of virtual glenohumeral bone loss reported 20% glenoid bone loss in combination with 6% humeral bone loss, or 10% glenoid defect and a 19% Hill-Sachs lesion as the critical amounts of bone loss in bipolar lesions creating instability (Walia et al. 2016). In a follow-up cadaveric study the authors concluded that 10% glenoid bone loss resulted in significant loss of stability in combination with 19% humeral head impression (Gottschalk et al., 2016). Similarly, a cadaveric study by Arciero and colleagues confirmed that bipolar bone loss has a negative additive effect on glenohumeral stability. A small (8%) glenoid defect was sufficient to significantly destabilize the joint in the presence of a medium-sized Hill-Sachs lesion, and small Hill-Sachs lesion sufficed to compromise a Bankart repair in the presence of 15% glenoid bone loss (Arciero et al., 2015). Di Giacomo and colleagues have emphasized the importance of including the role of glenoid bone loss in the glenoid track concept. Reduction of glenoid width may reduce the glenoid track width to such a level that a previously stable on-track lesion, becomes an unstable off-track lesion (Di Giacomo et al., 2014). Imaging studies have revealed the feasibility of predicting on-track and off-track lesions based on MRI images with satisfactory accuracy (Gyftopoulos et al., 2015). The presence of bipolar bone lesions has a significant impact on surgical indications and clinical outcomes as detailed further below.

Fig 2.5

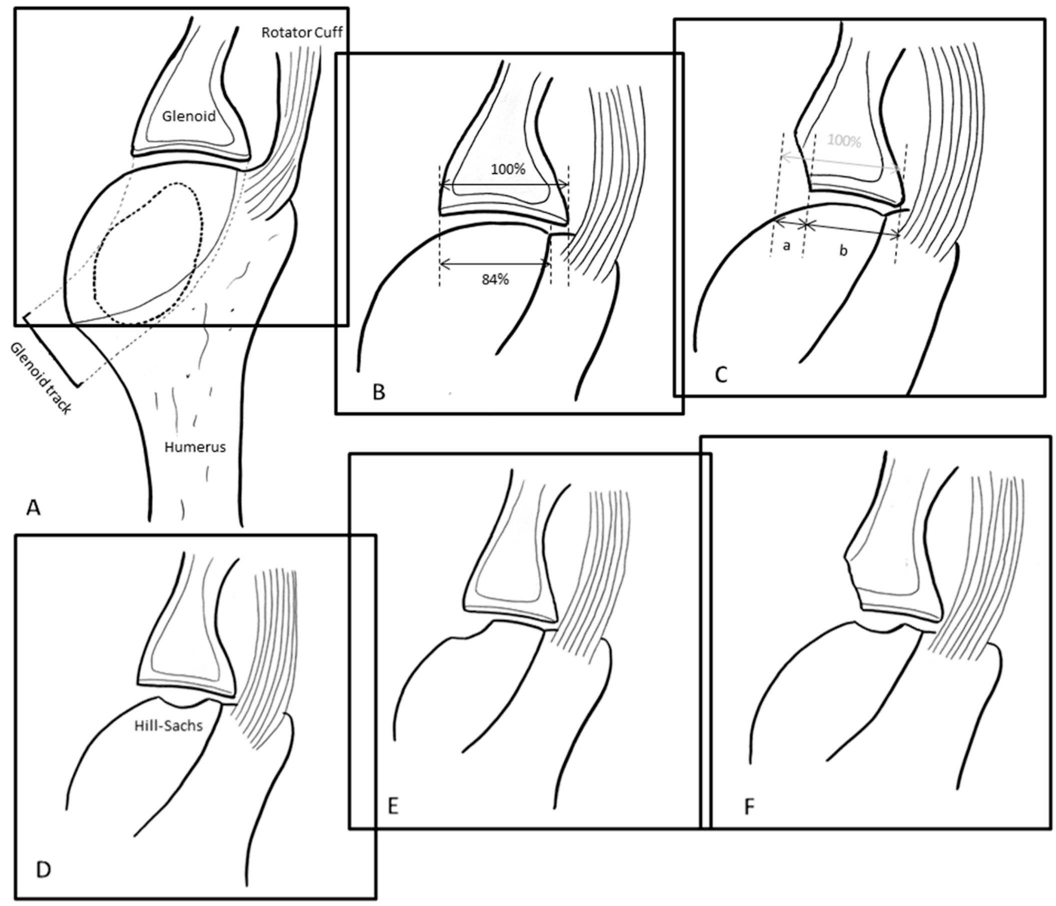


Figure 2.5
Illustrations depicting the glenoid track concept. In external rotation and abduction (A), the glenoid displaces the rotator cuff tendon, creating a glenoid track of approximately 84% of the glenoid width (B). In the presence of a glenoid rim defect, the defect width is subtracted from the 84% to calculate the actual glenoid track width (C). A Hill-Sachs lesion may be contained within the glenoid track and therefore considered an on-track lesion (D), or it may be large or medial enough to cause the humeral head to engage the glenoid in an off-track manner (E). An otherwise stable (on-track) humeral lesion may become unstable (off-track) in the presence of glenoid bone loss (F).

2.2 Treatment

2.2.1 Introduction

The treatment of shoulder dislocation, which aims to restore shoulder function to the pre-injured state of pain-free mobility and stability, includes conservative (non-surgical) and surgical management. Treatment of shoulder instability is generally preceded by the urgent reduction of the dislocated joint, followed by a period of rest, immobilization, and physiotherapy. Surgical treatment may involve open or arthroscopic procedures, soft-tissue or bony procedures, and is typically followed by a brief period of immobilization, followed by intensive physiotherapy.

2.2.2 Reduction

Reduction of the dislocated shoulder is considered an orthopedic emergency. More than 20 different methods have been described detailing how to reduce a dislocated shoulder. Although many variations exist, techniques usually involve longitudinal traction, rotation and gentle manipulation. Some methods employ countertraction at the axilla using the physician’s heel (Hippocratic method), the back of a chair, or a bedsheet (Matsen method)(Westin et al., 1995)(Ufberg et al., 2004). Other techniques follow a specific pattern of rotation, traction and manipulation as described by the original authors, such as the Milch, Kocher, Eskimo and Stimson manoeuvres (Milch, 1949)(Boger et al., 1980)(Kocher, 1870). Importantly, a number of techniques, including the Boss-Holzach-Matter method can be taught to patients, allowing them to self-reduce under supervision. The technique involves having the semi-flexed supine patient hook his bound wrists over his or her ipsilateral knee and recline gently (Boss et al., 1993). The literature offers little guidance as to which technique should be used. Multiple methods have been shown to be safe and effective, and it is generally advised to use whichever technique the physician is most accustomed to (Kuhn et al., 2006). However, forceful reduction by traction on the outstretched arm in combination with vigorous countertraction in the patient’s axilla by way of the physicians heel, such as in the Hippocratic method, is no longer recommended due to the risk of axillary neurovascular injury or humeral head fracture (Regauer et al., 2014).

Reduction manoeuvres can be performed in the non-sedated, sedated or locally anesthetized patient. Several authors have demonstrated shorter hospital stays, reduced complications and lower cost after intra-articular injection of local anesthetic, with the same reduction success ratio as after sedation (Kuhn et al., 2006)(Wakai et al., 2011). Our preferred technique involves gentle longitudinal traction of the limb with the patient in a dorsal decubitus position under sedation. The shoulder is abducted 30-45° and the surgeon's other hand is used to guide the humeral head laterally (Fig. 2.6). Careful post-reduction neurovascular exam should be performed and compared to the dislocated state and radiographic confirmation should always be obtained. Importantly, studies have shown that 37.5% of fractures associated with shoulder instability are only visible on x-ray after reduction (Kahn and Metha, 2007). In rare cases, due to soft-tissue interposition or bony injury, closed reduction is not successful and open surgery is required. Literature on such cases is limited to case reports (Gudena et al., 2011).

Figure 2.6

Figure 2.6
Our preferred technique for reduction of an anteriorly dislocated shoulder. The physician exerts slight longitudinal traction with one hand (orange arrow), while gently translating the proximal humerus and humeral head laterally with the other hand (white arrow).

2.2.3 Conservative treatment

Treatment after shoulder dislocation, in the absence of concomitant injuries requiring special attention, is primarily aimed at the prevention of recurrent dislocation. The incidence of recurrence after dislocation ranges from 14% to 100% in the literature, depending on multiple factors such as age, sex, sportive and professional activities, symptoms, previous instability, and pathological lesions (Boone and Arciero, 2010). After reduction, the patient is traditionally placed in a sling for 3 to 6 weeks depending on his or her age. Historical data has led to the commonly held belief that patients under 30 years old require longer immobilization regimens than do older patients (Kiviluoto et al., 1980). More recent research has shown, however, that immobilization beyond the first week has little to no effect on risk of recurrence after primary dislocation (Hovelius et al., 1996)(Kuhn et al., 2006)(Patterson et al., 2010).

Controversy over the optimal position of the shoulder during the immobilization period began after Itoi and colleagues suggested that labral healing might be improved by immobilizing the shoulder in external rotation (Itoi et al., 2001). The underlying philosophy being that external rotation would aid in reducing the medialized avulsed CLC, as well as increase the pressure of the subscapularis tendon on the CLC during healing. Biomechanical and imaging studies on the topic have yielded conflicting evidence, and the topic remains contested (Limpisvati et al., 2008)(Seybold et al., 2009). A large meta-analysis performed by Whelan could not find any benefit of external over internal rotation, as pertaining to functional outcomes, risk of recurrence or compliance to therapy (Whelan et al., 2016). However, some authors have continued to advocate for immobilization in external rotation, especially in cases with evidence of medialized capsulolabral structures on imaging studies (Murray et al., 2018).

After reduction and immobilization, most patients are referred to a physiotherapist to assist in the rehabilitation of the shoulder. Evidence surrounding physiotherapy is limited, but usually involves restoration of pain-free range of motion, and strengthening of the rotator cuff and periscapular musculature followed by sports-specific rehabilitation. In professional athletes, physiotherapy and accelerated rehabilitation have shown a return to play in 73% of athletes after 5 days for in-season instability events. Yet, only 27% of players managed to finish the season without recurrence (Dickens et al., 2014).

Contrary to multidirectional shoulder instability, long-term follow-up of primary traumatic shoulder dislocation has revealed an unacceptably high rate of recurrence in young and active patients when treated solely with rehabilitation (Kirkley et al. 2005)(te Slaa et al., 2004). These findings have led to a paradigm shift in the management of acute traumatic shoulder instability. Similarly to cruciate repair surgery in the knee, the urgency and necessity of surgical repair after shoulder dislocation in athletes and other high demand patients is becoming more apparent. Studies have shown recurrence rates of 37.5% overall (Longo et al., 2014), and up to 75% and 80% in high-demand patients (Arciero et al., 1994)(Bottoni et al., 2002). In contrast with previous decades when surgical stabilization was usually put off until the second dislocation, increasingly, surgeons argue for immediate surgical stabilization for high-risk patients. Conversely, patients with multidirectional instability, joint hyperlaxity and elderly patients are still preferentially treated nonoperatively (Bofano et al., 2017). The use of stabilizing shoulder braces has been advocated by some, and may be beneficial in non-overhead athletes. However, the cumbersome and restricting harnesses are not compatible with most overhead athletic activities (Reuss et al., 2004).

2.2.4 Surgical Treatment

2.2.4.1 History

One of the oldest recorded methods of surgical treatment for shoulder instability was described by Hippocrates of Cos in 440 BCE. Hippocrates advised cauterization of the skin, especially in the axillary region, followed by immobilization of the shoulder, in the hope of inducing scarification (Adams, 1886). With the advent of modern surgical technology and anesthesiology, the surgical foundations for the current treatment of traumatic anterior shoulder instability were laid down. At the end of the 19th century, Eduard Albert performed the first recorded shoulder arthrodesis in a patient suffering from recurrent shoulder instability (Van der Linde et al., 2015). Perthes first described the reattachment of the CLC to the anterior glenoid rim in 1906, although the method was only really popularized by Bankart in 1923 (Somford et al. 2017). This type of procedure quickly surpassed contemporary techniques such as the Putti-Platt and Magnuson-Stack procedures. In the Putti-Platt technique, the humeral head was tethered to the glenoid by fusing a 2.5cm segment of subscapularis tendon to the anterior glenoid neck. The Magnuson-Stack procedure, on the contrary, involved transferring the lesser tuberosity to an area below the greater tuberosity in an effort to tighten the anterior structures and forego external rotation. Despite the diminished risk of recurrence, the resulting loss of motion, complications and risk of early arthropathy rendered these techniques ultimately undesirable (Rockwood and Matsen, 2009).

The use of open bone block procedures such as the Bristow, Latarjet, Eden and Hybinette techniques also fell out of favour temporarily due to concerns over early joint degeneration. However, as discussed below, bone grafting procedures have come back to the forefront, owing to the recent reappreciation of the role of bone loss in glenohumeral instability (Van der Linde, 2016). Procedures such as the Trillat osteotomy which involve rotation of the coracoid process to shorten the subscapularis muscle and to block anterior dislocation, or the Oudard osteotomy which involved coracoid lengthening by graft interposition, have largely been abandoned and are mentioned only out of historical relevance. Similarly, proximal humeral osteotomies and glenoid neck osteotomies are seldom indicated. The latter may be experiencing a revival in the light of increased awareness of glenoid version abnormalities (Aygun et al., 2016)(Hohman and Tetsworth, 2015). Thanks to the emergence of arthroscopy, multiple classically open stabilizing techniques have been converted to arthroscopic procedures in the hope of minimizing surgical invasiveness and maximizing rehabilitation.

2.2.4.2 Indication

In a landmark study, Hovelius and colleagues reported that 25 years after conservative treatment for primary shoulder dislocation, only half of the patients younger than 25 years at the time of dislocation, had remained stable without surgery (Hovelius et al., 2008). The same study group also reported a 39% incidence of moderate/severe glenohumeral arthropathy in the recurring non-stabilized population, which was significantly higher than in the surgically stabilized group (p=0.047). The study also indicated that surgically stabilized shoulders had the same incidence of arthropathy as solitary dislocators, disproving the theory that surgical stabilization inevitably leads to degeneration. Mather calculated, using the data from the Hovelius and Bottoni studies, that patients younger than 18 years old, had 77% percent risk of recurrence within the first year, and 68% chance of instability at 10 years (Mather et al., 2011). Similarly in a prospective randomized trial, Jakobsen and colleagues found a recurrence rate of 54% at 2 years, 62% at 10 years and a dissatisfaction rate of 74% in the nonoperatively treated group, compared to a 3% recurrence at 2 years, a 7% recurrence at 10 years and a 72% good/excellent results in the surgically stabilized group (Jakobsen et al., 2007). All patients were younger than 40 years in the latter trial. Due to the significant impact of recurrent shoulder instability on pain, apprehension, quality of life, risk of early degenerative disease and economic or athletic repercussions, the threshold for surgical treatment in young and active patients is being lowered. The timing and type of surgery for traumatic anterior shoulder instability is still the topic of considerable debate.

2.2.4.2 Soft-Tissue procedures

2.2.4.2.1 Lavage

Most soft-tissue procedures aim to restore CLC function after traumatic disruption. A minimally invasive lavage of joint effusion is believed to aid in the alleviation intra-articular effusion and restoration of the labrum to the correct position. Wintzell and colleagues reported a reduction in recurrence rate of 53% in young patients one year after lavage, when compared to conservative treatment (Wintzell et al., 1999). However, longer term follow-up studies have reported a sharp increase in recurrences after the first year mark (te Slaa et al., 2005). Later studies definitively showed the superiority of labral repair compared to lavage in double blind randomized controlled trials (Robinson et al., 2008)(Chahal et al., 2012).

2.2.4.2.2 Arthroscopic Capsuloligamentolabral repair

Arthroscopic Bankart repair is currently the most commonly performed shoulder stabilization procedure (Flinkkila et al., 2015). The so-called Bankart repair was introduced by Perthes, but independently popularized by Bankart at the start of the 20th century as an open capsulolabral repair using transglenoid tunnels to reattach the anterior structures (Somford et al., 2017). Several variations were introduced later, including a titrated amount of capsular plication, depending on the laxity and elongation of the capsule and ligaments (Altcheck et al., 1991). Despite early reports of unacceptably high recurrence rates and poor clinical outcomes using arthroscopic techniques, a clear trend towards all-arthroscopic procedures has become evident in recent years. Poor initial results have been linked to non-anatomic repairs and suboptimal instrumentation and fixation devices (Pope et al., 2011). Ever since the initial discrepancy in outcomes, several publications have demonstrated the equivalence between open and arthroscopic CLC repair. This is, in part, believed to be due to improved techniques and materials (Harris et al., 2013)(Zaffagnini et al., 2012)(Owens et al., 2015).

Suture repair is commonly performed using bone anchors. Anchor designs and materials may vary, and clinical outcomes have been related to specific devices (Imhoff et al., 2010). Surgical techniques depend on surgeon preference, yet the lateral decubitus position has proven popular for arthroscopic stabilization procedures. The classic posterior, anterior and “skybox” portals offer a 360° view of the glenoid, allowing surgical stabilization of anterior and posterior structures if necessary (Li et al., 2015). No matter what position, portals or instruments are used, a full release and lateralization of the scarred and medialized CLC is necessary before reimplantation on the glenoid rim. With the aid of specialized instruments, the surgeon encircles the CLC with suture material and reduces the labrum and capsule to the glenoid rim by tying the structures to the anchor. Opinions are divided on the ideal position of the repaired labrum. Some have advocated positioning the labrum on the glenoid face, whereas others favour a more anatomical position on the glenoid rim itself (Park et al., 2018)(Yamamoto et al., 2013). Overall, clinical results after arthroscopic Bankart repair have been excellent. As mentioned earlier, a clear benefit of labral repair has been shown, compared to conservative treatment or arthroscopic lavage. In a prospective randomized trial, Kirkley and colleagues found a significantly lower rate of redislocation amongst athletes under 30 years old after arthroscopic labral repair (Kirkley et al., 2005). Recent meta-analyses have shown recurrence rates of 8% to 18% (Harris et al., 2013)(Voos et al., 2011). However, longer follow-up studies have demonstrated a steady increase of redislocations after the traditional 2 year benchmark. Van der Linde reported a 35% recurrence rate after 8 to 10 years. Nearly half of these redislocations seem to occur 2 years after the stabilization, and almost a quarter after 4 years (Van der Linde, 2011)(Bessiere et al., 2014).

Several factors have been found to influence the risk of recurrence after Bankart repair. Technical aspects such as the position and number of anchors play a role. Studies have shown that Bankart repairs using less than 3 anchors have an increased risk of earlier recurrence (Van der Linde, 2011)(Boileau et al., 2006). Excessive medialization of bone anchors is thought to be incompatible with restoration of the glenoid labrum and has shown inferior biomechanical results (Ho et al., 2016)(Yamamoto et al., 2013). Similarly, “high” (superior) placement of the most inferior anchor on the glenoid rim is believed to result in less favourable outcomes (Ho et al., 2016). However, a large-scale meta-analysis could not confirm the findings related to these technical aspects of Bankart surgery (Brown et al., 2017). More importantly, patient characteristics such as renewed trauma, age, gender, hyperlaxity, number of dislocations preoperatively, sports participation, as well as glenoid and humeral bone lesions have been associated with worse outcomes after Bankart repair (Boileau et al., 2006)(Ho et al., 2016). Age seems to be the most important predictor for recurrent instability. Several studies have indicated higher risks of recurrence in younger patients after Bankart repair (Porcellini et al., 2009)(Voos et al., 2010)(Imhoff et al., 2010)(Balg and Boileau, 2007). Patients younger than 20 years old exhibited a relative risk increase of 35% compared to their older counterparts in one systematic review (Randelli et al., 2012). Male gender has also been associated with higher risk of recurrence after CLC repair. Randelli and colleagues calculated a twofold increase in recurrence compared to female patients (Randelli et al., 2012). Both Boileau and Voos reported a three-fold increase in recurrence in patients with shoulder laxity (Boileau et al., 2006)(Voos et al., 2010). Some studies comparing Bankart repair after first-time and recurrent dislocators have shown significant increases in recurrence and revision rates in the recurrent population (Marshall et al., 2017)(Lee et al., 2018), while others have shown equivalent outcomes (Grumet et al., 2010). Sports participation, type of sport and level of sport have also been the subject of intense study. The absence of a universally accepted classification of sports types contributes to the confusing and conflicting literature. Nevertheless, it is generally accepted that high energy, contact, collision and overhead sports increase the risk of recurrence (Balg and Boileau, 2007). Increasingly, the role of glenoid and humeral bone loss in the risk of recurrence after soft-tissue repair, is being recognized. This topic will be discussed in the section on bony procedures below.

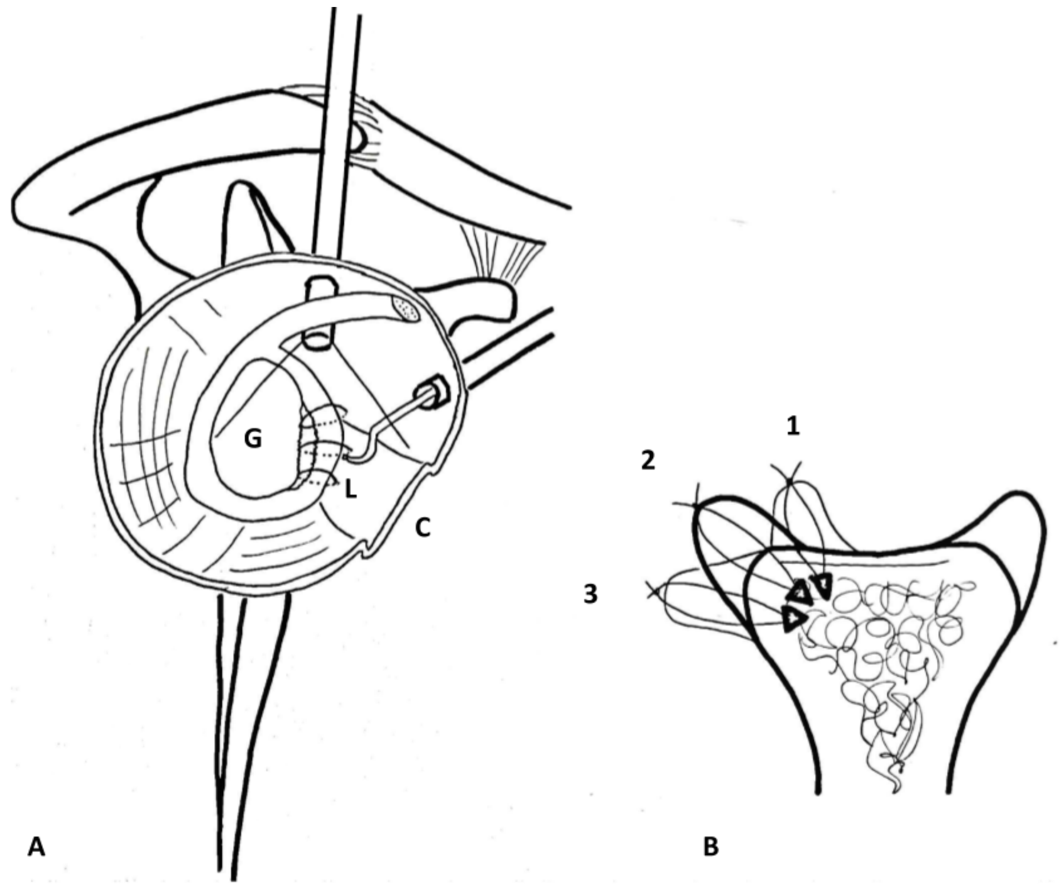


Figure 2.7
Drawing of arthroscopic Bankart repair. Panel A. offers an "en face" view of the scapula. The glenoid (G), labrum (L) and capsule (C) are shown. The figure illustrates the labrum and capsule being sutured with a specialized arthroscopic instrument inserted via an anterior portal. The light source and camera are inserted through the superior portal for visualization. Panel B. is a representation of an axial slice through the glenoid. Three modes of labral

repair are shown: on the glenoid face (1), on the glenoid rim (2), and on the glenoid neck (3). The glenoid rim repair is preferred by most authors.

2.2.4.2.3 Open Capsuloligamentolabral repair

The advantages of arthroscopic repair include smaller skin incisions, shorter surgical procedures, thorough arthroscopic examination, less postoperative pain, decreased narcotic usage, decreased complication rates and improved shoulder motion. Disadvantages include a technically demanding technique, longer learning curve and dependence on technical innovations and devices (Levy et al., 2016). Despite the attractiveness of arthroscopic procedures and the general trend towards arthroscopic stabilization worldwide, a subset of surgeons still advocate for open Bankart procedures with capsular shift. Chalmers and colleagues performed a systematic review of meta-analyses on the topic. The author’s overall conclusions confirmed the equivalence between open and arthroscopic techniques. However, a clear discordance between analyses published before 2007 and after 2008 is apparent. This possibly reflects advances in arthroscopic technology, excluding obsolete capsular reattachment techniques such as transglenoid tunnels and tacks. The authors also warn against the risk of confusing recurrent subluxation and frank dislocation (Chalmers et al., 2016).

Nevertheless, many mainly North-American and Japanese authors still perform open Bankart procedures with capsular shift in higher-risk patients and athletes. The procedure involves approaching the glenohumeral joint through the deltopectoral interval, releasing the subscapularis muscle and incising the joint capsule along a laterally based T outline. After performing a Bankart repair when necessary, the superior and inferior capsular flaps are closed in a pants over vest style suture technique (Fig. 2.7)(Pollock et al., 2000). Comparing open and arthroscopic Bankart procedures solely using bone anchors, Miura and colleagues found no difference in recurrent dislocation, but a significantly higher rate of subluxation and apprehension in the arthroscopic population (Miura et al., 2008). Similarly, Virks and colleagues found a significantly shorter time to recurrence after arthroscopic Bankart and capsulorraphy, compared to open repair. The authors therefore still support open Bankart and capsular shift in heavy duty labourers and athletes (Virks et al., 2016). Conversely, the recognition of risk factors such as age, gender, activity, hyperlaxity and presence of bone loss, has led many to opt for more invasive bony procedures such as the Latarjet and Bristow in those types of cases. Especially in Europe, the debate over open capsular repair is largely hypothetical since the threshold for bone procedures is significantly lower.

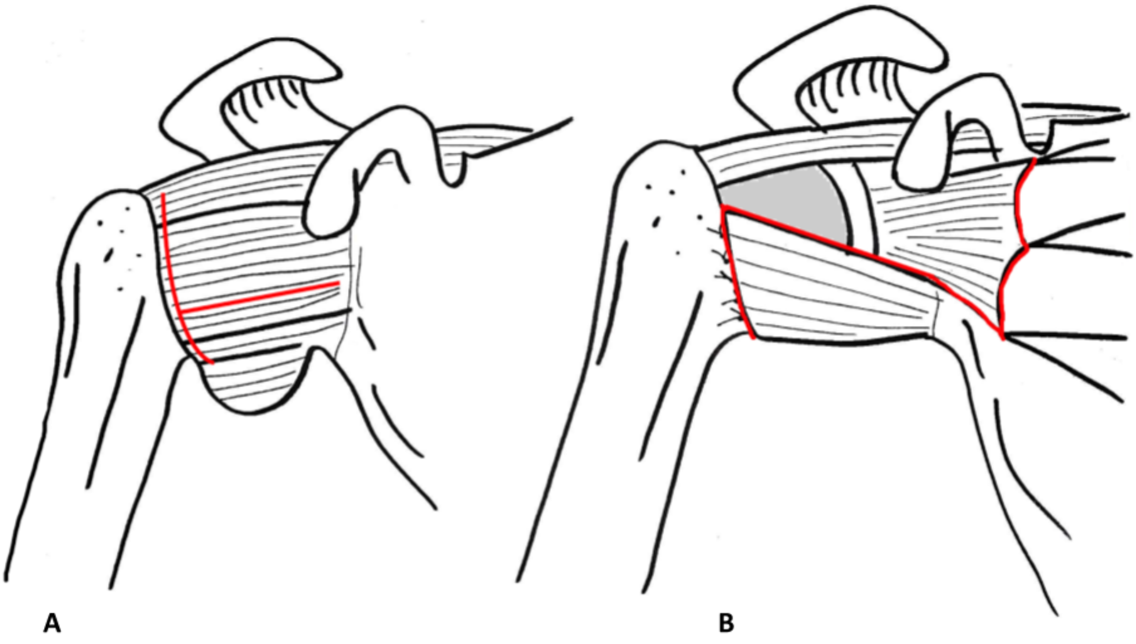


Figure 2.8
Drawing of open capsular shift. Panel A. shows the incision (red) in the capsule of a right shoulder joint. Panel B. shows the same shoulder after tightening the inferior capsular flap and preparing to tie the superior flap in a pants-over-vest manner.

2.2.4.2.4 Concomitant soft-tissue lesions

Several additional lesions may be found during arthroscopy for anterior shoulder instability. These include RI laxity, SLAP, HAGL, GLAD and rotator cuff tears. As mentioned in the anatomy section, the RI is an area of capsular tissue spanning the distance between the superior edge of the subscapularis and the anterior aspect of the supraspinatus. Two distinct structures within the RI are the CHL and superior GHL. Laxity of the RI is associated with glenohumeral instability (Field et al., 1995). Closure of the RI during open or arthroscopic surgery has been advocated in the setting of multidirectional instability, hyperlaxity or mild forms of instability. The closure is believed to tighten the capsule and reduce intracapsular volume. Although there is a role for RI closure in the aforementioned cases, the literature has shown no benefit when combined with Bankart repair and capsulorraphy in cases of acute unidirectional instability (Maman et al., 2017). SLAP lesions and pan-labral tears should be actively looked for and repaired when necessary (Forsythe et al., 2015). Similarly, surgeons should be heedful of HAGL lesions, and repair them when required. Some studies have indicated that the presence of GLAD lesions predisposes patients to a higher risk of failure after Bankart repair, although the mechanism is not well understood (Pogorzelski et al., 2018). As mentioned above, rotator cuff lesions may occur as a result of shoulder instability. Rotator cuff tears have a much greater incidence in older patients and often require surgical attention. Most of the concomitant lesions mentioned above call for lesion-specific treatment. However, a detailed description of the diagnostics and treatment strategies is not included due to the constraints of breadth and scope of this thesis (Forsythe et al., 2015).

2.2.4.2.5 Remplissage

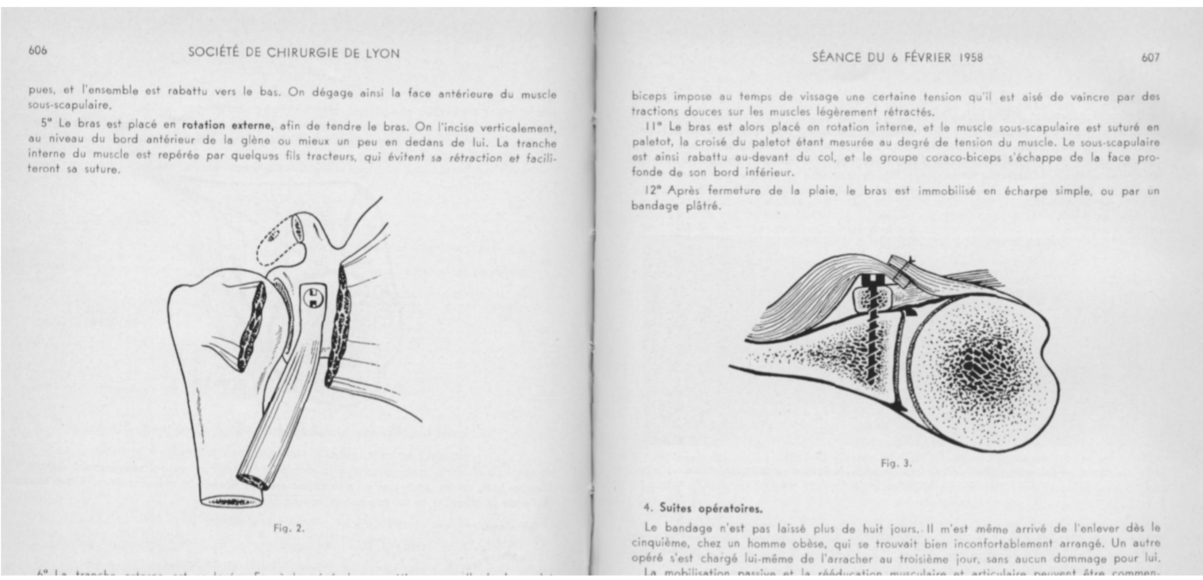
The remplissage procedure, named after the french "remplir" or "to fill", was first described by Purchase in 2008 as a solution for engaging Hill-Sachs lesions. The technique involves performing an arthroscopic tenodesis of the infraspinatus tendon in the Hill-Sachs lesion, thus filling the void and precluding engagement of the lesion on the anterior glenoid rim (Purchase et al., 2008). Satisfactory clinical results have been reported using this method. Wolf and Arianjam published a 4.4% recurrence rate at 58 months, while Garcia and colleagues reported a 11% rate at 5 year follow-up (Wolf and Arianjam, 2014)(Garcia et al., 2016). Despite reassuring results including high outcome scores and high percentages of athletes returning to sports, many surgeons remain concerned about the potential loss of external rotation associated with remplissage, especially in overhead athletes (Elkinson et al., 2012). Garcia et al. demonstrated a 95% return to sports, with 81% returning at the same level, despite a 5.26° loss of external rotation. In the study's breakdown of sports types, contact sports and throwing sports had less favourable return percentages compared to other types (Garcia et al., 2016). Several meta-analyses have reported successful outcomes combining Bankart repair surgery and remplissage, even in the presence of subcritical glenoid bone loss (<20%). Camus and colleagues calculated a 4-fold decrease in risk of recurrent instability when combining remplissage with Bankart repair, compared to performing an isolated Bankart repair (Brilakis et al., 2018)(Liu et al., 2018)(Camus et al., 2018). Most authors agree to forego Bankart repair and remplissage in cases involving significant glenoid and/or humeral bone loss in favour of bone grafting procedures (Yang et al., 2018). However, recent case reports and technical notes have demonstrated the feasibility and potential of combining remplissage and Latarjet procedures in patients with large Hill-Sachs lesions and significant anterior glenoid bone loss (Katthagen et al., 2016). However, longer-term studies are required to fully understand the clinical role of remplissage combined with anterior glenoid bone grafting.

2.2.4.3 Bony Procedures

2.2.4.3.1 History

Some confusion exists surrounding the naming conventions of anterior glenoid bone grafting techniques. The so-called "Bristow-Latarjet" procedure refers to a transposition of the coracoid process to the anterior glenoid neck. One such technique was taught by sir Walter Rowley Bristow, an English surgeon in the early 20th century, who despite never publishing a description of the procedure himself, was immortalized in the technique's eponym 19 years after teaching it to his South-African student Arthur J. Helfet. In 1958, Helfet published the details of the surgical procedure in which the terminal centimeter of the coracoid process was taken off and transposed to an abraded area of anterior glenoid neck through a vertical slit in the subscapularis. The graft was then secured in place by suturing the conjoint tendon to the subscapularis. Although the underlying mechanism was not very well understood, the graft and conjoint tendon were believed to "reinforce" the joint and act as a buttress. Helfet warned against the use of hardware to attach the graft to the glenoid, recounting troublesome non-unions in cases in which metal devices were implanted (Helfet, 1958)(Van der linde, 2015). Independently of this, Michel Latarjet, son of the renowned French anatomist and surgeon André Latarjet, published a technique of coracoid transplantation for recurrent shoulder instability in 1954. Interestingly, the technique was published simultaneously with the Trillat technique of coracoid osteotomy, in the same edition of the same journal (Van der Linde, 2015). However, in Latarjet's technique, which he refined in 1958, the entire subscapularis was taken down, the injured labrum resected and the glenoid neck abraded, before the pre-drilled coracoid process was transferred and screwed to the scapular neck. Latarjet emphasised the augmentation of the glenoid surface, the secure fixation of the graft and the subscapularis imbrication afterwards (Fig. 2.8)(Latarjet, 1958).

In the literature, the eponym Bristow is generally used to denote a procedure involving a small bone graft in an on-end position and one screw fixation, whereas the name Latarjet refers to a larger coracoid fragment fixed with two screws in a "lying-down" position (Giles et al., 2014). Hovelius used the name "Bristow-Latarjet" to describe his method for coracoid transfer using one cortical screw in an "on-end" position, with the osteotomized cancellous bone apposed to the abraded glenoid (Hovelius et al., 1983). Michel Latarjet didn't mention Bristow or Helfet in his original paper, but did refer to publications by Eden and Hybbinette. Both authors described treating recurrent shoulder instability with the aid of free anterior glenoid bone grafts. Rudolf Eden published a technique inserting a tibial corticocancellous graft under the scapular periosteum in 1917, while Oscar Samuel Hybbinette reported using an iliac crest graft in 1932. Neither author described the use of fixation devices during these procedures. The techniques were aimed at restoring glenoid bone loss, but also at mechanically blocking or buttressing anterior translation of the humeral head. The eponymous "Eden-Hybbinette" technique became synonymous with free bone grafting of the anterior glenoid and popular in scandinavian countries (Van der Linde, 2015). As discussed below, the original techniques were modified by later generations of surgeons.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pues, et l'ensemble est rabattu vers le bas. On dégage ainsi la face antérieure du muscle sous-scapulaire.

5° Le bras est placé en **rotation externe,** afin de tendre le bras. On l'incise verticalement, au niveau du bord antérieur de la glène ou mieux un peu en dedans de lui. La tranche interne du muscle est repérée par quelques fils tracteurs, *qui évitent sa rétraction et faciliteront sa suture.*

Fig. 2.

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biceps impose au temps de vissage une certaine tension qu'il est aisé de vaincre par des tractions douces sur les muscles légèrement rétractés.

11° Le bras est alors placé en rotation interne, et le muscle sous-scapulaire est suturé en paletot, la croisé du paletot étant mesurée au degré de tension du muscle. Le sous-scapulaire est ainsi rabattu au-devant du col, et le groupe coraco-biceps s'échappe de la face profonde de son bord inférieur.

12° Après fermeture de la plaie, le bras est immobilisé en écharpe simple, ou par un bandage plâtré.

Fig. 3.

4. Suites opératoires.

Le bandage n'est pas laissé plus de huit jours. Il m'est même arrivé de l'enlever dès le cinquième, chez un homme obèse, qui se trouvait bien inconfortablement arrangé. Un autre opéré s'est chargé lui-même de l'arracher au troisième jour, sans aucun dommage pour lui.

Figure 2.9
Excerpt from Michel Latarjet 1958 publication on coracoid transplantation. Latarjet M. (1958). *[Technic of coracoid preglenoid arthroereisis in the treatment of recurrent dislocation of the shoulder]*. *Lyon chirurgical*, *54*(4), 604–607.

2.2.4.3.2 Coracoid Transfers

The Bristow type procedures have shown satisfactory results in long-term studies. Schroder and colleagues reported a 15.4% recurrence rate, with a 9.6% redislocation rate after 26.4 years using this technique in 52 shoulders (Schroder et al., 2006). Hovelius et al. published their results of a similar procedure in 319 shoulders over a period of 30 years. The authors reported a recurrence rate of 13% and redislocation rate of 5%. An overall satisfactory or excellence rating was given by 96% of patients despite a relative reduction in external rotation. Loss of external rotation was more pronounced in satisfied patients compared to very satisfied patients (Hovelius et al., 2012). Radiographic follow-up of these patients indicated that grafts placed too medially or too high, were associated with greater recurrence rates. Five out of the six patients with medialized grafts exhibited redislocation. One possible method of avoiding high or low positioning of the graft on the glenoid neck, is harvesting a larger graft. This modification comprises the added benefit of allowing more than one screw for graft fixation, which increases the rotational stability of the construct (Hovelius et al., 2012). A similar modification of the Latarjet procedure was introduced by Didier Patte in 1980, and later popularized by Gilles Walch (Fig. 2.9)(Patte and Debeyre, 1980)(Joshi et al., 2015). Patte theorized that the coracoid transfer procedures increased stability via the “triple locking mechanism”. This mechanism proposed increased stability via bony augmentation of the glenoid surface, dynamic stabilization through the sling effect of the conjoint tendon, and capsular reinforcement by incorporation of the coracoacromial ligament stump in the repair (Patte and Debeyre, 1980). Walch and Boileau reported a 1% recurrence in 160 shoulders after 3 years, with 98% good or excellent rating, using this technique (Walch and Boileau, 2000). Allain and colleagues recorded no recurrences after 14.3 years in 95 shoulders. (Allain et al., 1998). Such results stood in sharp contrast with the high recurrence rates of soft-tissue procedures mentioned earlier.

Conversely, coracoid transfer procedures have always been associated with a higher risk of complications, chief amongst these, the risk of early glenohumeral arthritis. Hovelius reported a 23% moderate and 11% severe osteoarthritis prevalence, 33 to 35 years after coracoid transfer (Gordins et al., 2015). The same researchers published a 17% moderate and severe degeneration prevalence amongst unoperated but stable patients, and 38% in unoperated and unstable patients, 25 years after primary dislocation. The study, moreover, indicated that surgically stabilized patients only exhibited that severity of degeneration in 26%, suggesting a possible protective role of surgery (Hovelius et al., 2016). Using the Latarjet technique, Allain et al., reported a 10.3% rate of moderate to severe arthritis after a mean of 14 years. Several studies found excessive lateral placement of the coracoid graft to be associated with osteoarthritis (Allain et al., 1998)(Walch and Boileau, 2000). Lädermann and colleagues evaluated the risks of arthropathy 16 years after single-screw Latarjet procedure. Findings included a higher risk in patients older than 40 years old at the time of surgery and lateral graft placement, whereas hyperlaxity appeared to have a protective influence (Lädermann et al., 2013).

To address these issues, Burkhart and de Beer published a modification in the year 2000, which involved rotation of the graft 90° around its long axis before affixing it to the glenoid. This rotation no longer places the curved undersurface of the coracoid against the glenoid neck, but flush with the glenoid articular surface, in the hope of increasing overall construct congruity (de Beer and Roberts, 2010). Burkhart reported a 4.9% recurrence rate at 59 months using the modified technique (Burkhart et al., 2007). Burkhart and de Beer were also the first to introduce the concept of the inverted pear shaped glenoid. The authors reported an unacceptable failure rate of 67% after Bankart repair in cases with anterior bone loss. The appearance of severe anterior glenoid bone loss during arthroscopy was said to resemble an inverted pear during arthroscopy (Burkhart and de Beer, 2000). These results further cemented our understanding of the need for anterior glenoid bone grafting in high risk cases with anterior glenoid bone loss or engaging Hill-Sachs lesions. As will be discussed in the following chapter, extensive biomechanical research has investigated the stabilizing properties of several modifications. However, there is no direct clinical evidence in the literature indicating a reduction in the incidence of osteoarthritis when using the congruent-arc modification.

Coracoid transfer procedures fell out of favour in the 1990’s in the United States after several studies reported on the risks of loss of motion, early osteoarthritis and complex revision surgery in cases of failed coracoid transfer (Young and Rockwood, 1991). As discussed more in-depth in Chapter 5, coracoid transfer procedures are associated with a higher risk of severe neurovascular injury, hardware complications and complex revision surgery compared to Bankart repair techniques (Griesser et al., 2013). However, in light of the high failure rates using soft-tissue procedures and the unacceptable risk of early osteoarthritis in cases of untreated shoulder instability (Hovelius et al., 2016), bone grafting techniques have been the topic of ongoing research and development. In 2007 Laurent Lafosse published an all-arthroscopic Latarjet technique which involved an anterior capsulectomy and coracoid transfer via a subscapularis split and fixation with two screws (Lafosse et al., 2007). Similarly, in 2010 Boileau and colleagues described an all-arthroscopic Bristow procedure, fixing the coracoid tip in an on-end position using one screw. Importantly, many of these techniques do not advocate for separate capsular repair using the CAL as in open techniques (Boileau et al., 2010). The arthroscopic adaptations have shown promising results with only a 1-3% recurrence rate (Dumont et al., 2007). They are however, technically demanding and associated with a long learning curve (Moga et al., 2017). Hardware complications have since led to further innovations and modifications described in Chapter 6.

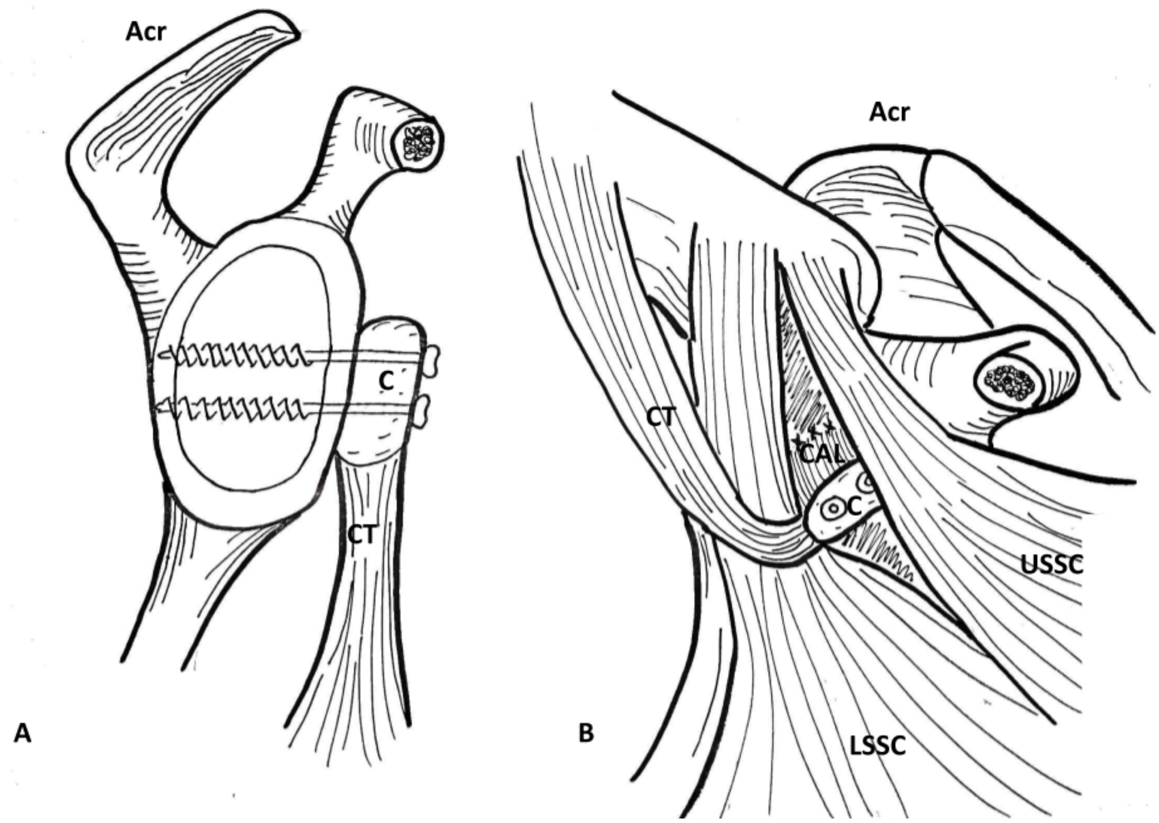

Figure 2.9
Drawings of the Bristow-Latarjet procedure. Panel A. offers an en face view of the glenoid after coracoid transfer. The figure shows the transferred coracoid (C) process fixed to the glenoid via two cortical screws through a subscapularis split. The osteotomized coracoid stump is shown, as well as the acromion (Acr). In Panel B. the shoulder is seen from the front. The graft is seen positioned between the upper and lower part of the subscapularis split (USSC and LSSC). In abduction and external rotation, the conjoint tendon crosses the inferior part of the subscapularis to reinforce the anteroinferior quadrant via the so-called "sling effect". The coracoacromial ligament (CAL) is shown after being sutured to the capsule remnant anteriorly. Drawings adapted from *The latarjet procedure for recurrent anterior shoulder instability: Rationale and technique, Edwards B. and Walch G. Operative Techniques in Sports Medicine*, *Volume 10, Issue 1, January 2002, Pages 25-3.*

2.2.4.3.3 Iliac Crest Grafting

Iliac crest bone grafting of the anterior glenoid, referred to by the eponym Eden-Hybbinette, was introduced by Palmer and Widen in 1948. The authors proposed extending the anterior glenoid rim using a structural iliac crest graft to prevent intracapsular subluxations caused by Hill-Sachs lesions (Palmer and Widen, 1948). The iliac crest inner table was thought to match the glenoid articular contour, to be easily accessible for harvest, to be associated with a low risk of significant complications, and to allow further contouring when necessary (Hutchinson and Dall., 1994)(Almaiman et al., 2013). The procedure gained enormous popularity in Scandinavia in a modified form, known as the "Alvik" procedure. This method consisted of press-fitting a preshaped fragment of corticocancellous crest into the anterior glenoid neck (Niskanen et al., 1991). Relatively high recurrence rates, loss of motion, and reports of early postoperative glenohumeral arthrosis led to a limited adoption of the technique outside of Northern Europe. Rahme and colleagues reported a 20% recurrence rate and a 47% prevalence of osteoarthritis, although only 16% of these were moderate to severe arthritis and mostly non-symptomatic according to the authors (Rahme et al., 2003). Similarly, Niskanen reported a 21% recurrence rate and degenerative changes in 52% of cases (Niskanen et al., 1991). Inconsistencies in outcome reporting and historical bias have made it impossible to reconstruct whether the incidence of osteoarthritis was indeed higher, and if so, whether it was the result of the procedures or part of the predictable post-dislocation arthropathy. Moreover, it is unclear to what degree authors intended to use the bone graft as an actual “block” to anterior humeral translation, versus as an extension of the glenoid arc. As discussed in Chapter 3, prominent graft placement may have played a role in the high rates of postoperative degenerative changes.

More recent publications on Eden-Hybbinette using hardware fixation have indicated acceptable recurrence rates and reassuring postoperative radiographic evolution. Warner and colleagues reported no recurrences in 11 patients followed for 33 months and satisfactory postoperative motion and imaging (Fig 2.10)(Warner et al., 2003). Steffen and Hertel described only 1 recurrence in 43 patients followed for 9.2 years. The study demonstrated satisfactory clinical results and stabilization of osteoarthritic changes. Technically, the procedure differs from the one described by Warner et al. regarding placement of the graft. Hertel’s procedure advocated for an extracapsular position of the graft, whereas Warner’s closed the capsule medially to the graft, making it an intracapsular construct (Steffen and Hertel, 2013). The debate regarding the biomechanical and biological effects of these variations is ongoing and discussed in Chapter 3.

Interestingly, despite the seeming unattractiveness of the Eden-Hybbinette technique as a primary procedure, it has long been recognized as the most valid revision option for failed coracoid transfers. Lunn and colleagues reported 79% good or excellent results in their series of 34 patients revised after failed prior stabilization. Only 4 (11.7%) patients recurred after a mean follow-up of 6.8 years. Moderate or severe osteoarthritis was seen in 17.6% of cases (Lunn et al., 2008). Similarly, 28 of the 43 patients in the study by Steffen and Hertel mentioned above were revision cases (Steffen and Hertel, 2013). We published a paper in 2015 outlining our technique for revision of a failed Latarjet procedure using a free tricortical iliac crest graft based on these aforementioned techniques (Willemot et al., 2015). Although described in more detail in Chapter 5., the surgical procedure involved careful dissection of the scarred anatomy of the anterior shoulder in the absence of the traditional landmarks (i.e. coracoid process and conjoint tendon). The shoulder was approached through a classic deltopectoral incision, usually via the previous skin scar. The subscapularis muscle was identified and split in a lateral to medial fashion, making sure not to stray medial of the coracoid stump to avoid injuring the neurovascular structures. Depending on the context of the procedure, the remnants of the coracoid process and conjoint tendon were debrided or tagged for later reimplantation. The technique described in the article is a relatively universal amalgam of Eden-Hybbinette variants and consists of fixation of a tricortical iliac crest bone autograft with the iliac inner table facing laterally. The publication of this article as a separate surgical technique with accompanying video was felt to be relevant because of the unfamiliarity of many surgeons with the technical challenges of revision surgery after prior open shoulder stabilization. Open revision surgery has shown acceptable results in our series, as well as in the literature mentioned above (Willemot et al., 2019)(Lunn et al., 2008)(Steffen and Hertel, 2013). However, results are far from excellent and much remains unknown about the exact indication and technical execution of revision bone grafting. The paper is included below (Addendum 2.1).

In recent years, the Eden-Hybbinette procedure has gained notoriety under the name anterior “iliac crest bone grafting” (ICBG). New techniques have emerged which allow arthroscopic or mini-open introduction and placement of iliac crest grafts under arthroscopic control. Technique pioneers such as Ettore Taverna and colleagues have demonstrated successful treatment of high risk patients by arthroscopic ICBG with 88% satisfaction, limited loss of motion (4.4°), high bony graft union (92%) and no recurrences at 2 year follow-up (Taverna et al., 2018). Similarly, Markus Scheibel and collaborators have shown high satisfaction, consistent bony healing and no recurrence in 15 patients at 2 years follow-up using an all-arthroscopic ICBG technique (Kraus et al., 2014). In the 1980’s, the Austrian researcher Herbert Resch started developing his modification of the Alvik procedure, which he called the “J-bone” procedure (Auffarth et al., 2008). This technique is still in use today and involves the harvesting of a J-shaped piece of corticocancellous iliac crest which is impacted in a chiselled through in the anterior glenoid neck. One of the main advantages of the J-bone technique is the stable graft fixation without the need for hardware. As such, proponents aim to avoid many of the hardware and graft-related problems seen after Bristow-Latarjet such as graft fracture, non-union, resorption and hardware irritation or breakage (Griesser et al., 2013)(Gupta et al., 2015). Excellent outcomes have been reported using this technique in 47 shoulders after 18 years. A subjective shoulder score of 90%, minimal loss of motion, one recurrence and 12% moderate to severe arthropathy were reported in a recent publication by Moroder and colleagues (Moroder et al., 2018). The J-bone technique has since been adapted to an all-arthroscopic technique (Anderl et al., 2016).

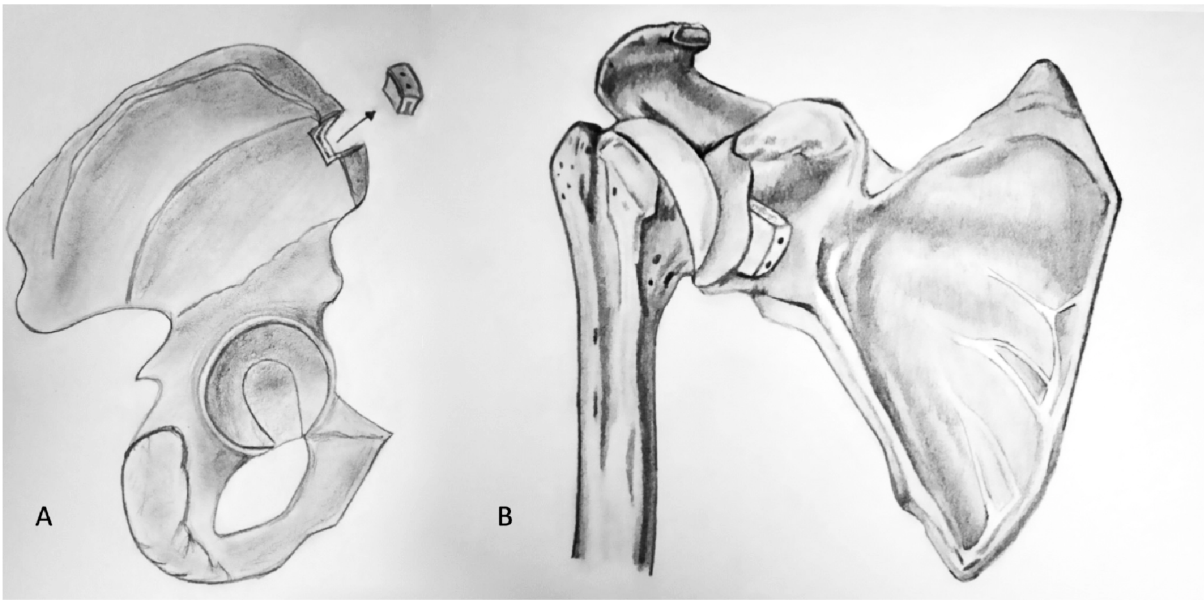

Figure 2.10
Drawing of an Eden-Hybbinette procedure. Panel A. shows the harvest of a tricortical graft from the iliac crest. Panel B. shows placement of the iliac crest on the anterior glenoid. *Willemot et al., (2019). Analysis of failures after the Bristow-Latarjet procedure for recurrent shoulder instability. International Orthopaedics. http://doi.org/10.1007/s00264-018-4105-6*

2.2.4.3.4 Bony Bankart repair

When a bony Bankart fragment is present, open or arthroscopic fixation may be attempted in an effort to reduce the risk of recurrent dislocation. Small fragments can be incorporated in a standard Bankart repair using a straightforward arthroscopic anchor-based transosseous technique, while larger fragments may require open surgery using cannulated screws or more complex bridging suture methods (Millet et al., 2009)(Kim et al., 2009)(Zhang et al., 2011). The ideal treatment method for medium-sized fragments is yet undetermined (Godin et al., 2018). Although bony Bankart repair is typically preferred in acute cases, mixed results have been reported adopting these techniques for chronic fragments, and outcomes may be less predictable than primary coracoid transfer or ICBG techniques (Mologne et al., 2011)(Plath et al., 2015)(Sugaya et al., 2006)(Porcellini et al., 2007). Severe resorption of glenoid bone fragments is often seen within the first year when left untreated (Nakagawa et al., 2013). In such cases, the amount of fractured and attritional bone loss may be underestimated. The literature comparing bony Bankart repair to primary bone grafting is scarce.

2.2.4.3.5 Hill-Sachs treatment

Various surgical techniques have been described for the direct treatment of Hill-Sachs lesions. Humeroplasty, or disimpaction of a humeral compression fracture may be possible in the setting of an acute Hill-Sachs lesion. Both classic bone tamps and balloon humeroplasty techniques have been shown to work in cadaveric specimen (Kazel et al. 2005)(Ratner et al., 2016). However, due to the potential risk of avascular necrosis and neurovascular injury, the techniques have not yet gained acceptance in the orthopedic community. Moreover, disimpaction of the Hill-Sachs lesion does not restore the damaged humeral cartilage. Remplissage techniques can be used in isolation or combined with glenoid-sided procedures as described earlier. Humeral head bone grafting with the help of osteochondral bone plugs or size-matched allografts has been described by several authors (Kropf and Sekiya, 2007) (Chapovsky and Kelly, 2005)(Tang et al., 2017). However, the available literature consists of small series and case reports. Alternatively, restoration of the humeral head defect using a metal prosthetic may be a viable treatment option in some cases (Besette et al., 2017)(Moros and Ahmad, 2009). Comparative literature on this type of treatment is scarce. In extremely severe cases or after failed reconstruction, hemi or total prosthetic replacement may be the only workable solution (Patel et al., 2014). Most of these humerus-specific techniques are beyond the subject matter of this thesis and are not discussed in further details. Harkening back to the topic at hand, some authors have proposed extending the glenoid arc with bone grafts as a preventative measure against engaging and off-track humeral lesions. However, as will be discussed in Chapter 5., augmentation of the glenoid surface beyond the physiologic dimensions is not without risk of complications (Moroder et al., 2012)(Di Giacomo et al., 2011).

2.3 Indications for Anterior Glenoid Bone Grafting

Improved understanding of the pathoanatomical changes associated with recurrent shoulder instability has shifted the emphasis from soft-tissue procedures to bony surgical stabilization. It is well recognized that recurrent shoulder instability is associated with glenoid, humeral and bipolar bone loss (Griffith et al., 2008). Moreover, traditional capsulolabral repairs have been proven insufficient in the treatment of patients with significant bone lesions, with failure rates of up to 67% (Balg and Boileau, 2007)(Burkhart and de Beer, 2000)(Tauber et al., 2004). Traditional surgical guidelines recommend treating glenoid bone loss exceeding one third of the glenoid width (Rockwood and Matsen, 2007). However, this figure is largely subjective and not well substantiated. Biomechanical studies have suggested a critical level of glenoid bone loss of 15% to 25% of the glenoid width (Yamamoto et al., 2009)(Shin et al., 2015), and clinical studies have corroborated cut-off levels between 13.5% and 17.3% of glenoid width (Shaha et al., 2015)(Shin et al., 2017). However, a consensus on the maximally allowable amount of glenoid bone loss has not been reached.

Furthermore, significant humeral bone lesions are known to interact with the glenoid in a process called engagement (Burkhart and de Beer, 2000). These interactions were later redefined as “on-track” or “off-track” in the glenoid track concept put forth by Yamamoto and colleagues (Yamamoto et al., 2007). Off-track humeral lesions have been observed to significantly increase the risk of recurrence in shoulder instability patients (Shaha et al., 2016). Significant glenoid bone, engaging or off-track humeral lesions and high risk bipolar lesions constitute the main indications for anterior glenoid bone grafting. The most popular forms of grafting are divided in non-anatomic coracoid based techniques and possibly more anatomic, so-called, “free” bone graft techniques which include the iliac crest grafts and other autologous and allogeneic grafts as discussed in Chapter 4. Both groups are associated with certain advantages and disadvantages depending on the graft and technique used, yet the coracoid based Bristow-Latarjet methods are believed to offer inherently more stability due to the conjoint tendon sling effect as discussed in the next Chapter (Yamamoto et al., 2013)(Wellmann et al., 2013). Conversely, the non-anatomic nature of the coracoid transfer, the significant technical challenges and learning curve of arthroscopic Latarjet, combined with the success of free iliac crest grafts in revision cases of failed Latarjet procedures, have fuelled the quest for more anatomic, less invasive and equally successful free bone grafting procedures. This has led to a surge in academic interest in the indications, biomechanics, complications and outcomes of free bone block procedures, in the treatment and prevention of traumatic anterior recurrent shoulder instability.

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Addenda

Addendum 2.1:

Revision of a Failed Latarjet Procedure Using an Open Tricortical Iliac Crest Autograft. Technique. Laurent Willemot, MD, Geert Declercq, MD, and Olivier Verborgt, MD, PhD. Techniques in Shoulder and Elbow Surgery 2015;16: 69–73.

Revision of a Failed Latarjet Procedure Using an Open Tricortical Iliac Crest Autograft Technique

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Abstract: Treatment of recurrent pain and instability after coracoid transfer procedure is a complex problem. This paper and accompanying video (Supplemental Digital Content 1, http://links.lww.com/TSES/A19) describe the surgical technique for revision of a failed Bristow-Latarjet procedure using a tricortical iliac crest autograft. The case presented here is a 32-year-old male with painful anterior subluxations after a Latarjet procedure because of coracoid graft pseudarthrosis. Surgical technique and result of the case are presented.

Key Words: failed Latarjet procedure, instability, revision, iliac crest autograft, glenohumeral instability

(*Tech Should Elb Surg* 2015;16: 69–73)

Treatment options for recurrent anterior shoulder instability vary from soft-tissue repair to bone grafting procedures such as the Bristow-Latarjet. Because of the triple blocking mechanism,[1] the Bristow-Latarjet-type procedures have shown a significant and reliable reduction in recurrence rates compared with soft-tissue techniques.[2–6] Nevertheless, due to graft fracture, pseudarthrosis or resorption, instability may recur.[7] These rare cases sometimes require repeat bone grafting to ensure a fully stable shoulder joint. Most frequently, open bone grafting using an iliac crest autograft is the preferred method of treatment. The technique first described by Eden[8] and Hybinette[9] made use of a bicortical graft, whereas some authors have since modified the procedure; using a tricortical iliac crest graft instead.[10,11] In the case of revision surgery after Bristow-Latarjet, the absence of surgical landmarks and extensive scarring represent a significant technical challenge to the surgeon.[12]

MATERIALS AND METHODS

Patient Information

The patient presented here is a right-hand-dominant 32-year-old male suffering from painful anterior instability of the left shoulder after undergoing a Latarjet procedure. The patient had sustained an acute traumatic anterior dislocation 2.5 years earlier and had been treated with a coracoid process transfer procedure because of recurrent instability in the presence of a significant glenoid bone defect. Initially, the patient, a heavy manual laborer, quickly regained function and strength. After the first year, however, the pain reoccurred and the patient experienced several subluxations. Upon presentation at our institution, range of motion was normal but a clear apprehension and relocation sign were evoked during physical examination. Radiographic imaging revealed pseudarthrosis of the coracoid graft (Figs. 1, 2). In this paper and video (Supplemental Digital Content 1, http://links.lww.com/TSES/A19), we aim to describe an open surgical technique for revision of failed Latarjet using a tricortical iliac crest autograft.

Surgical Technique

Surgery is performed with the patient in beach chair position. The arm is draped free to allow intraoperative rotation and abduction of the shoulder. A small pillow is placed between the shoulder blades allowing more facile access to the anterior glenoid neck. Draping should also include a window to the ipsilateral iliac crest. Video 1 (Supplemental Digital Content 1, http://links.lww.com/TSES/A19) and Table 1 describe the procedure in a chronological order.

Step 1: Approach

The skin incision is made at the site of the previous scar (Fig. 3). Dissection is carried through the subcutaneous tissues with electrocautery until the deltopectoral interval is identified. Deep subcutaneous dissection is executed with care as the extensive scarring as well as the absence of important surgical landmarks such as the coracoid process and the cephalic vein can complicate this otherwise relatively straightforward approach. Once the interval is located, it is developed further by blunt finger dissection. A Bankart retractor is placed in the deltopectoral interval and a Hohmann retractor is positioned at the superior edge of the subscapularis muscle tendon to reveal a wide overview of the underlying anatomic structures. In the absence of the traditional landmarks, the subscapularis muscle is defined superiorly by the Hohmann retractor, laterally by the intact insertion, and inferiorly by the circumflex humeral artery. The heavily scarred-in subscapularis muscle is released, carefully avoiding straying medially of the coracoid stump (Fig. 4). The subscapularis muscle is then split with electrocautery at the lower 1/3 of the muscle belly. The division is carried laterally into the subscapularis tendon preserving the underlying joint capsule (Fig. 5). After releasing the subscapularis muscle from the underlying structures superiorly and inferiorly, the joint capsule is exposed and a vertical capsulotomy is made at the level of the glenoid rim. A Steinmann pin is placed to retract the superior part of the subscapularis muscle, a 2-pronged curved retractor is placed medially on the scapular neck, and a Fukuda retractor is inserted to reveal the glenoid articular surface.

Step 2: Debridement of the Coracoid Remnant

Scar tissue overlying the anterior glenoid neck is removed with electrocautery until both fixation screws are identified (Fig. 6). The remaining scar tissue is released from the

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Supplemental Digital Content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Website, www.shoulderelbowsurgery.com.

FIGURE 1. Anteroposterior radiograph of the left shoulder 2.5 years after Latarjet procedure. Neutral (A) and external rotation (B) of the humerus. Fibrous nonunion of the graft is suspected. Note the presence a significant Hill-Sachs lesion.

FIGURE 2. Axial slice computed tomography image of the same left shoulder 2.5 years after Latarjet procedure demonstrating unicortical screw penetration and fibrous union of the coracoid graft.

coracoid graft with the aid of a periosteal elevator. Both screws are removed and a Hohmann retractor is placed at the inferior edge of the coracoid graft. A chisel and a rongeur are used to debride the coracoid remnant until healthy bleeding glenoid bone is encountered (Fig. 7). Care is taken not to resect the inferior coracoid tip, in an attempt to preserve the conjoint tendon sling effect.

Step 3: Graft Harvesting

A tricortical bone graft is taken from the anterior iliac crest approximately 5 cm from the anterior superior iliac spine with an oscillating saw. The anterior and posterior cuts are made 2 cm apart with a straight blade (Fig. 8), the inferior cut is made with a 90-degree–angled blade 1 cm below the crest. Drill holes (2.75 mm) for future screw fixation on the glenoid neck are made while the graft is still in situ (Fig. 9). Graft harvest is completed with an osteotome. Care is taken to mark the concave inner table for future orientation.

Step 4: Graft Positioning

The graft is placed on the anterior glenoid neck, with the concave inner table on the articular side. Provisional fixation is obtained by inserting a 1.6-mm Kirschner pin through the inferior drillhole (Fig. 10). Care is taken to position the graft flush with the glenoid articular surface. When satisfactory alignment is obtained, the graft is fixed with a second Kirschner pin (Fig. 11). The inferior hole is drilled with a

TABLE 1. Key Steps and Pearls of the Procedure

Techniques	Key Steps	Pearls
Preparation	Free draping of the arm with access to the iliac crest	A small pillow between the scapulae allows for better access to the glenoid
Superficial exposure	Deltopectoral approach. Bankart and Hohmann retractors are used to achieve sufficient overview.	The subscapularis muscle is not released medial to the coracoid stump
Deep exposure	Subscapularis split retracted by Steinmann pin superiorly, Fukuda retractor laterally, and a 2-pronged curved retractor medially	Careful dissection of the subscapularis from the capsule allows for vertical capsulotomy and layered closure
Coracoid debridement	Use of electrocautery, chisel, and rongeur until bleeding glenoid bone is found	The inferior pole of the coracoid graft is left in situ to preserve the sling effect
Graft harvest	Anterior and posterior cuts made with a straight saw, inferior cut with an angled sawblade	Graft is left in situ until drillholes have been made. The concave inner side of the graft should be marked for future orientation.
Graft positioning	Temporary fixation with Kirschner pins	Graft is placed flush with glenoid articular surface
Closing	Layered closing of capsule, subscapularis, and deltopectoral interval	Closure with the arm in external rotation to avoid overtightening

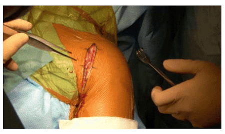

FIGURE 3. Draped left shoulder. The skin incision is made at the site of the previous scar.

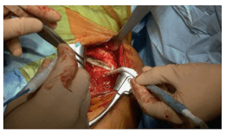

FIGURE 5. The subscapularis muscle is split with electrocautery at the lower 1/3 of the muscle belly.

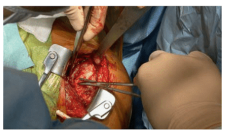

FIGURE 4. In the absence of traditional landmarks, the subscapularis muscle is defined superiorly by the Hohmann retractor, laterally by the intact insertion, and inferiorly by the circumflex humeral artery. The heavily scarred-in subscapularis muscle is carefully released.

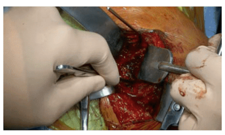

FIGURE 6. A curved 2-pronged retractor is inserted medially and a Fukuda retractor laterally. Both screws are identified after removing the scar tissue overlying the anterior glenoid neck with electrocautery.

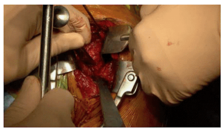

FIGURE 7. Debridement of the coracoid remnant with chisel and rongeur until healthy bleeding glenoid bone is encountered.

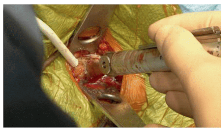

FIGURE 8. Anterior and posterior cuts in the iliac crest are made 2 cm apart with a straight blade.

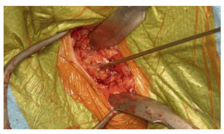

FIGURE 9. Drillholes for future screw fixation on the glenoid neck are made while the graft is still in situ.

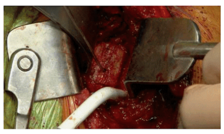

FIGURE 10. Provisional fixation of the iliac crest graft with a Kirschner pin on the anterior glenoid neck.

FIGURE 11. After correct positioning is achieved, the graft is temporarily fixed with a second Kirschner pin.

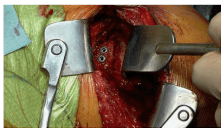

FIGURE 12. Definitive graft fixation on the anterior glenoid neck with cannulated screws.

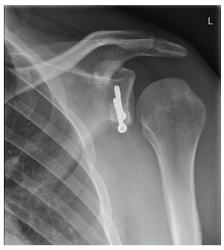

FIGURE 13. Postoperative anteroposterior radiograph. Flush positioning of the iliac crest graft on the anterior glenoid neck.

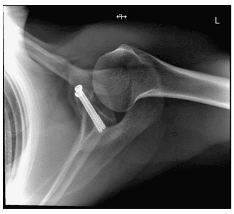

FIGURE 14. Postoperative axillary view radiograph. Flush positioning of the iliac crest graft on the anterior glenoid neck with bony union.

2.75-mm cannulated drill, and a 4.5-mm cannulated screw of the appropriate length is inserted (standard length: 34 to 36 mm). The procedure is repeated for the superior drillhole (Fig. 12). The stability of the construct is tested manually intraoperatively.

Step 4: Closing

When graft position and fixation are deemed adequate, the joint is copiously irrigated and closed. The capsule is closed separately with the arm in external rotation to avoid overtightening. The subscapularis split is partially repaired with double stitches of resorbable material. The deltopectoral interval is approximated with simple sutures.

RESULTS

Postoperative Status

The patient was immobilized in a neutral sling for 4 weeks. Passive mobilization was allowed within the safe zone (anteflexion <90 degrees; external rotation <0 degrees). Afterwards, formal active rehabilitation was begun. Radiographic imaging demonstrated satisfying graft positioning postoperatively (Figs. 13, 14). After 1 month, the patient reported pain relief and no apparent stiffness. After 3 months, the patient demonstrated painless full range of motion. Standard x-rays including an axillary view at this time showed adequate graft positioning and bony union. The patient returned to full manual labor after 3 months. There have been no reports of recurrence at the final follow-up after 1 year.

DISCUSSION

This paper describes the surgical technique of a modified Eden-Hybinette procedure involving the grafting of a tricortical iliac crest autograft to the anterior glenoid neck as a salvage procedure for failed Bristow-Latarjet procedure. Recurrent instability after Bristow-Latarjet is a complicated problem. Although arthroscopic treatment has been suggested for cases of failed Bristow-Latarjet with successful outcomes,[13] failure is sometimes believed to be related to graft fracture, pseudarthrosis, resorption, or harware failure. In cases where repeat bone grafting is deemed necessary (eg, the contact athlete), glenoid augmentation with an iliac crest autograft is the gold standard. Young and Rockwood[12] described revision surgery after Bristow-Latarjet as "complex and difficult," yet in this paper we aim to describe a straightforward open revision technique for the treatment of such cases. The technique described here restores glenoid width while leaving the conjoint sling intact. The graft is placed under direct vision to insure correct flush positioning which is believed to be an important factor in the prevention of early omarthrosis. Surgeons should be aware of the loss of anatomic landmarks and the extent of postoperative scarring. Neurovascular structures are typically displaced due to the nonanatomic nature of the Bristow-Latarjet procedure and can cause serious complications if this is not taken into account. In summary, we aim to present the surgical technique for revision of a failed Latarjet procedure by open tricortical iliac crest bone graft augmentation of the anterior glenoid rim.

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Chapter 3: Biomechanics of Bone Block Procedures

“Late at night a policeman sees a drunk man on all fours, patting the ground under a street lantern, and asks him what he is doing. The man tells him that he has lost his keys, and together they continue looking for them. After a few minutes the policeman inquires where exactly the man thinks he lost his keys, and the man replies that he lost them in the park nearby. The surprised policeman then asks him why he isn’t looking for them over there, and the man replies, "because the park doesn’t have any street lights, they would be impossible to find”.”

As retold by Dr. Kai-Nan An, 2013.

Overview

This chapter provides a in-depth review of current knowledge regarding biomechanical mechanisms of bone block procedures for shoulder instability. The results of our own biomechanical experiments are also included in this chapter, detailing our research into the stabilizing effects of iliac crest bone grafts on intact glenoids, and the development of a formula for predicting 2D kinematic behaviour of glenohumeral surfaces based on articular morphology.

3.1 Cadaveric Biomechanical Studies

3.1.1 Glenoid Bone Loss

As explained in Chapter 1, the concavity-compression mechanism governs glenohumeral stability in the midrange of motion (Matsen et al., 1991). When glenoid concavity constraint is diminished by anterior glenoid bone loss, increasingly more effort is required by the rotator cuff muscles to stabilize the joint during motion. Itoi and colleagues demonstrated this in a landmark paper in which they created stepwise increments of antero-inferior glenoid bone loss on cadaveric shoulder specimen and analyzed the reactive translational forces on the humeral head during active compression of the glenohumeral joint. The authors found that in the midrange of motion, a defect measuring 21% of the glenoid length or 28% of the glenoid width resulted in a statistically significant drop in translation force. Interestingly, in the endrange of motion position, the tightly repaired antero-inferior capsule prevented any such loss of stability (Itoi et al., 2000). In a follow-up experiment, the authors adjusted the location of glenoid bone loss from antero-inferior to anterior, adopting the findings of Sugaya and colleagues in regards to glenoid morphology of recurrent shoulder instability (Sugaya et al., 2003). This second study found that when bone loss was situated directly anterior, a defect measuring 25% of glenoid width critically decreased the joint's stability (Yamamoto et al., 2009).

Further research indicated that replacing the lost bone with an anterior glenoid bone graft could restore shoulder stability. Montgomery and colleagues noted the influence of the graft's contour on the balance stability angle, which is the maximal angle a glenoid can be tilted to from the vertical position before a metal sphere placed in the glenoid concavity dislocates over the anterior glenoid rim. Medially placed grafts did not entirely restore balance stability angle compared to flush grafts, and more laterally placed grafts were noted to push the metal ball posteriorly and increase the shoulder stability angle beyond the normal range (Montgomery et al., 2005). Yamamoto et al. pointed out that, in their experiment, the graft acted as a reconstruction of lost glenoid depth, arc and surface, and not as a "bone block to translation" as it has sometimes been described in the Bristow-Latarjet literature (Weaver and Derkash, 1994). Therefore, the authors preferred using the term glenoidplasty to "bone block procedure" for articular surface restoration using a bone graft (Yamamoto et al., 2010). Significant anterior bone loss is also known to reduce the contact area between the glenoid and humerus, to double the overall mean contact pressure, and increase anteroinferior glenoid contact pressure by 300-400% (Greis et al., 2002). This is believed to play a role in the development of early onset arthropathy in cases of anterior glenoid bone loss (Hovelius et al., 2016). Conversely, studies have shown that iliac crest and coracoid bone grafts have the ability to normalize contact area and contact pressure when positioned flush with the glenoid articular surface. Grafts positioned 2 mm proud result in contact pressure increasing up to 250% and posteroinferior loading, while medial graft positions increased antero-inferior edge loading (Ghodadra et al., 2010). As mentioned earlier, clinical studies have corroborated these findings. Proud graft positions have been linked to early degenerative changes and medial graft placement has been associated with higher rates of recurrence (Allain et al., 1998)(Walch and Boileau, 2000)(Hovelius et al., 2012)(Lädermann et al., 2013).

3.1.2 Coracoid Process Transfer

Several studies have investigated the mechanical principles behind the coracoid process transfer procedures. As discussed earlier, Patte theorized a triple locking mechanism in the '80s consisting of (1) the bony extension of the glenoid arc, (2) the ligamentous reinforcement of the anterior capsule by incorporation of the coracoacromial ligament (CAL), and (3) the stabilizing influence of the conjoint tendon crossing over the inferior part of the subscapularis muscle, and forming the so-called dynamic "sling-effect" (Patte and Debeyre, 1980). Wellmann and colleagues attempted to verify this theory by systematically deconstructing Bristow-Latarjet procedures performed on cadaveric specimen with a bony Bankart lesion, while measuring translational distances in endrange and midrange positions with the help of a robotic arm. The authors reported the sling effect as being the dominant stabilizing factor, yet noted an important role for the CAL in anterior and inferior translation in the midrange of motion. Although relevant, the bone graft effect was considered to be of less importance. Notably, the authors did not entirely remove the bone graft, yet reduced it to a Bristow-sized coracoid tip (Wellmann et al., 2012). Similarly, Yamamoto described the results of translational force tests using the Mayo Clinic shoulder testing apparatus in cadaveric specimen following a step-by-step deconstruction of the Bristow-Latarjet technique after creation of a 26% glenoid defect (Yamamoto et al., 2013). The results indicated overall dominance of the conjoint sling effect. However, in the endrange of motion, no additional stability could be gained from increasing tension on the conjoint tendon. The authors determined that the difference in stability between the Bankart lesion condition and the Bristow-Latarjet condition was representative of the gain in “stability” in the endrange of motion. The experiment allocated 76-77% of the Latarjet stability to the conjoint sling effect and 23-24% to the capsular reconstruction. Conversely, in the midrange of motion, the authors defined the gain in stability as the difference between the bone defect condition and the Bristow-Latarjet condition. The results allocated 51% of the stabilizing effect to the conjoint tendon, and by elimination 49% to the glenoidplasty. The conjoint tendon loading protocol revealed a further increase of the sling effect to 62% under 30 Newtons of tendon load, with a proportional loss of glenoidplasty effect. Interestingly, in the endrange of motion the authors did not comment on the further loss of translational force after the creation of the bony Bankart lesion and did not allocate any stabilizing effect to the coracoid graft. Presumably, the authors did not consider glenoid bone loss relevant in the endrange of motion, as their previous research had indicated that even large glenoid defects could be stabilized by classic Bankart soft-tissue repair in endrange positions (Itoi et al., 2000).

Multiple studies have investigated the various modifications of coracoid transfer procedures currently in use. Nourissat et al. investigated the role of superior-inferior graft position on glenohumeral stability in intact glenoids and reported significantly more stability when placing the graft at the 4 o’clock position, compared to the 3 and 5 o’clock positions in a Latarjet type configuration. In a Bristow type construct, graft position did not seem to influence humeral translation significantly (Nourissat et al., 2015). Giles and colleagues designed a custom shoulder rig for cadaveric analysis of shoulder biomechanics. The study group compared a Latarjet type procedure with a Bristow type procedure in the intact state as well as 15% and 30% glenoid bone loss models. Interestingly, the reported study outcomes distinguished macro-instability (dislocation) from micro-instability (joint stiffness) for each condition. The findings demonstrated that the Latarjet condition consistently outperformed the Bristow in terms of joint stiffness, and that the difference between the techniques increased with incremental bone loss. The techniques were equally successful at preventing dislocation in the intact state, but the Latarjet showed significant superiority in joint stiffness and macro-instability in the bone loss conditions. Surprisingly, the authors described the effects of both procedures on range of motion and could not find any significant effects or trends in rotation or extension, except when the procedure was performed in the intact state. In the intact condition, the Bristow procedure offered significantly more rotation during abduction, compared to the Latarjet procedure (Giles et al., 2014).

Giles and colleagues used the aforementioned rig to further investigate the role of the conjoint sling in Latarjet type procedures. The study revealed a reduction in gross dislocations from 25% to 0% by loading the conjoint tendon in glenoids with a 30% defect. Joint stiffness was significantly higher in the loaded condition in neutral rotation, yet no difference was seen in the abducted externally rotated conditions, confirming the role of the sling effect in the midrange of motion (Giles et al., 2013). Despite the dominance of the sling effect permeating through most, if not all, of the biomechanical literature, a recent study by Payne and colleagues using Thay Q. Lee's experimental rig, demonstrated the inability of the conjoint tendon by itself to stabilize the humeral head during testing under higher loads (>40N) in the absence of a coracoid graft (Barrett Payne et al., 2016). These findings contradict earlier results by the same study group which could not find any differences when comparing a Bristow transfer to tendon-only transfer. The authors speculated that the larger coracoid stump and intact CHL remains may have confounded the results (Kephart et al., 2016). Moreover, Barrett Payne and colleagues noted a posterior displacement of the humeral head due to conjoint tendon tensioning during biomechanical tests. These unintended secondary effects may play a role in postoperative morbidity (Barrett Payne et al., 2015). The same research laboratory also investigated the biomechanics of performing a Latarjet procedure in glenoids without anterior glenoid bone loss. This experiment revealed a significant reduction in anterior, but not in inferior translation during the application of anterior force (Dines et al., 2013).

A biomechanical comparison of the classic and congruent arc Latarjet techniques on the Giles shoulder simulator demonstrated an equivalence in stabilizing effect and stiffness of both techniques, despite a significantly greater humeral translation before stabilization in the latter condition (Boons et al., 2013). Pressure mapping experiments have shown more uniform contact pressure distributions using the congruent arc technique compared to the classic Latarjet (Ghodadra et al., 2010). A recent cadaveric study demonstrated the congruent arc technique's ability to reconstruct defects up to 50% of glenoid width, compared to 36% in the classic Latarjet technique (Montgomery et al., 2017). A more detailed discussion of the morphological differences between anterior glenoid bone grafts is given in Chapter 4.

The debate regarding whether or not the anterior capsule should be repaired in Bristow-Latarjet procedures, and where it should be repaired to, is ongoing and has been investigated biomechanically. Researchers using the robotic arm of the Wellmann experiments have reported an increase in stabilization after CAL repair in abduction and neutral rotation, yet the relevance of capsular stability in the midrange of motion is disputed. A biomechanical study by Kleiner and colleagues could not replicate the role of CAL repair in glenohumeral stabilization. The authors did report a significant reduction in range of motion as a result of the procedure (Kleiner et al., 2016). Arthroscopic Latarjet techniques, which do not include a standard capsular repair, have shown excellent results (Dumont et al., 2014). Similarly, Hovelius didn't find any added beneficial effects of performing a capsulopexy at the end of his coracoid transfer (Hovelius et al., 2012). Nevertheless, some authors believe capsular repair to be necessary in the prevention of recurrent apprehension and micro-instability (Schulze-Borges, 2013). Similarly, Itoigawa and colleagues investigated the role of intra versus extracapsular graft positioning using the Mayo Clinic testing apparatus. The authors found a significant reduction in external rotation and significantly higher translational stability using the extracapsular position. However, the authors rejected the validity of the translational results, citing a lack of evidence for the role of capsular stability in the midrange of motion (Itoigawa et al., 2016).

3.1.3 Iliac Crest and Free Bone Grafting

The advantages of the iliac crest grafts include availability, limited restrictions on graft size, lower rates of harvest complications, and post-harvest customizability. However, the biomechanical properties of free bone graft procedures differ from those of the coracoid transfers. Wellmann and colleagues directly compared the Latarjet procedure to an ICBG using a robotic arm based testing apparatus. The results indicated significantly less anterior and antero-inferior translation in 60° of abduction after the Latarjet technique. The study showed a 374% decrease in translation, compared to 159% with the contoured bone block technique. The increased stability was attributed to the sling effect and capsular repair as opposed to an isolated bone block (Wellmann et al., 2009). Yamamoto and colleagues demonstrated the successful restoration of translational force using an osseous graft after the creation of a large anterior defect. The authors chose the coracoid instead of an iliac crest graft out of convenience, and the results are therefore not entirely extrapolatable. However, the study did underline the importance of recreating the native glenoid articular surface in depth, arc length and curvature (Yamamoto et al., 2010). In a follow-up study, Yamamoto and colleagues compared the Latarjet and Iliac crest bone grafts biomechanically. The authors concluded from the results that the conjoint sling was dominant in both midrange and endrange motion as discussed earlier (Yamamoto et al., 2013).

Pressure mapping studies have indicated more physiological results after ICBG compared to coracoid bone grafts, confirming the superiority of iliac crest grafts in articular reconstruction when placed and contoured correctly (Ghodadra et al., 2010)(Montgomery et al., 2005). A more recent study investigating the stabilizing effect of the J-Bone graft reported similar results using a custom-built testing table. The authors found increased peak translational forces after reconstruction of a large glenoid defect using the J-Bone technique, and normalization of the glenohumeral contact patterns. Moreover, the study revealed satisfactory graft fixation without the use of hardware, as discussed in more detail in Chapter 5. (Pauzenberger et al., 2017). Overall, biomechanical evidence for the superiority of coracoid transfer procedures is strong.

On the other hand, a study performed on the Giles shoulder simulator demonstrated significantly greater superior translation in Latarjet and congruent-arc Latarjet conditions compared to the free bone graft condition, which was explained by the sectioning of the CAL during coracoid transfer surgery (Degen et al., 2013). Furthermore, a comparative study investigating the effect of coracoid transfer on scapular function found a higher incidence of dyskinesia in patients after Latarjet procedure compared to ICBG. The release of the pectoralis minor and the different working lengths of the short biceps and coracobrachial muscle were believed to play a role in the development of postoperative scapular positioning problems (Carbone et al., 2015). Thus, the non-anatomic coracoid transfer procedures, seem to offer a greater degree of stability, exceeding the intact condition in certain cases, but may create unwanted biomechanical side-effects. Dines and colleagues investigated the role of coracoid transfers in patients without glenoid bone loss and found no effect of the conjoint tendon on inferior translation (Dines et al., 2013). Moreover, Barrett Payne and colleagues noted a posterior displacement of the humeral head due to conjoint tendon tensioning during biomechanical tests. It is unclear whether this is purely an in-vitro finding or not (Barrett Payne et al., 2015). We therefore speculated that patients without glenoid bone lesions might be better off with the more limited, yet satisfactory, stabilizing effect of a free bone graft. This led us to investigate the role of a free ICBG on glenohumeral stability in the absence of glenoid bone loss. The research presented below was performed at the Mayo Clinic in 2012-2013 and published as "*Iliac bone grafting of the intact glenoid improves shoulder stability with optimal graft positioning*" in the *Journal of Shoulder and Elbow Surgery* in 2014.

3.1.3.1 Introduction

Risk factors for recurrence of shoulder instability after standard arthroscopic Bankart repair have become more defined recently (Tauber et al., 2004)(Balg and Boileau, 2007)(Longo et al., 2014). Patient characteristics such as age, physical activity, as well as patho-anatomic lesions such as Hill-Sachs lesions, glenoid bone loss and joint hyperlaxity are associated with a higher risk of recurrence after standard capsulolabral repair (Balg and Boileau, 2007). This has led to an increased interest in bone block procedures such as the Bristow-Latarjet procedure for the treatment of high-risk patients with important anterior glenoid bone loss (Young and Rockwood, 1991)(Burkhart et al., 2007). Furthermore, various authors have suggested expanding the indication to patients presenting without significant bone loss, such as high-risk contact athletes, patients with engaging Hill-Sachs lesions, anterior labral periosteal sleeve avulsions (ALPSA) or joint hyperlaxity (Balg and Boileau, 2007)(Neyton et al., 2012)(Cerciello et al., 2012).

Reports of high complication rates however (Butt et al., 2012)(Griesser et al., 2013)(Young and Rockwood, 1991), have pushed recent research towards less complex or invasive alternatives to the classic Bristow-Latarjet procedure. Arthroscopic glenoid augmentations using either a free iliac crest autograft or a tibial or glenoid osteochondral allograft have already been described as a successful treatment option for high-risk patients (Scheibel et al., 2008)(Provencher et al., 2009)(Skendzel et al., 2011)(Gupta et al., 2013)(Taverna et al., 2014). However, biomechanical data on the effect of these procedures is sparse, particularly concerning cases without significant glenoid bone loss.

The purpose of this biomechanical cadaver study was twofold. First, to compare the effect of standard labral repair to free bone graft augmentation of the glenoid. Secondly, to investigate the influence of sagittal graft position on stability.

3.1.3.2 Materials and Methods

Eight fresh frozen cadaver shoulders (four male and four female donors) and three pairs of fresh frozen iliac crests (three male donors) were obtained from our institutional anatomic bequest program. The mean age at the time of death was 66.5 years (range: 54 to 87 years) for the shoulder donors, and 55.4 years (range: 51 to 61 years) for the iliac crest donors. There were 4 right and 4 left shoulders. Specimens from donors with a history of shoulder instability and specimens with radiological or clinical evidence of previous surgical treatment, advanced degenerative, traumatic or neoplastic disease were excluded.

Shoulders were thawed overnight before removing all soft tissues with the exception of labrum and articular cartilage, as has been described before (Itoi et al., 2000)(Halder et al., 2001)(Yamamoto et al., 2010). Removal of the capsule and glenohumeral ligaments was not deemed to compromise the integrity of the experiment because of their minimal role in midrange instability; rotator cuff action was simulated during all experimental procedures using compressive force on a custom testing apparatus (Soslowsky et al., 1997)(Blasier et al., 1997). The glenoids and humeri were potted in poly-urethane resin (Smooth-Cast® 65D, Smooth-on, Inc, Easton, Pa., USA) to allow fixation onto a custom testing apparatus (Figure 3.1)(Itoi et al., 2000)(Halder et al., 2001)(Yamamoto et al., 2010). Briefly, the testing device consisted of a load cell mounted on a programmable stepper-motor controlled x-y table driving motion in the superior-inferior (y-axis) and anterior-posterior (x-axis) direction. The humerus was mounted in the scapular plane to a sliding stage connected to a pneumatic cylinder at 60° of abduction and neutral rotation. This allowed free translation of the humerus in the medio-lateral (z-axis) direction while applying a constant (50 N) compressive force. A linear-position transducer (TR-50; Novotechnik, Stuttgart, Germany) was attached to the sliding device to register lateral movement of the humeral head along the z axis. The rate of displacement throughout the cycle was 2 millimeter per second. Data regarding displacement and force along the x, y, and z axes were sampled at a rate of 25 Hertz. During testing, the specimen was sprayed with saline every 10-15 minutes. Experiments were conducted at room temperature (24°C). Bovine serum was applied to lubricate the articular surfaces

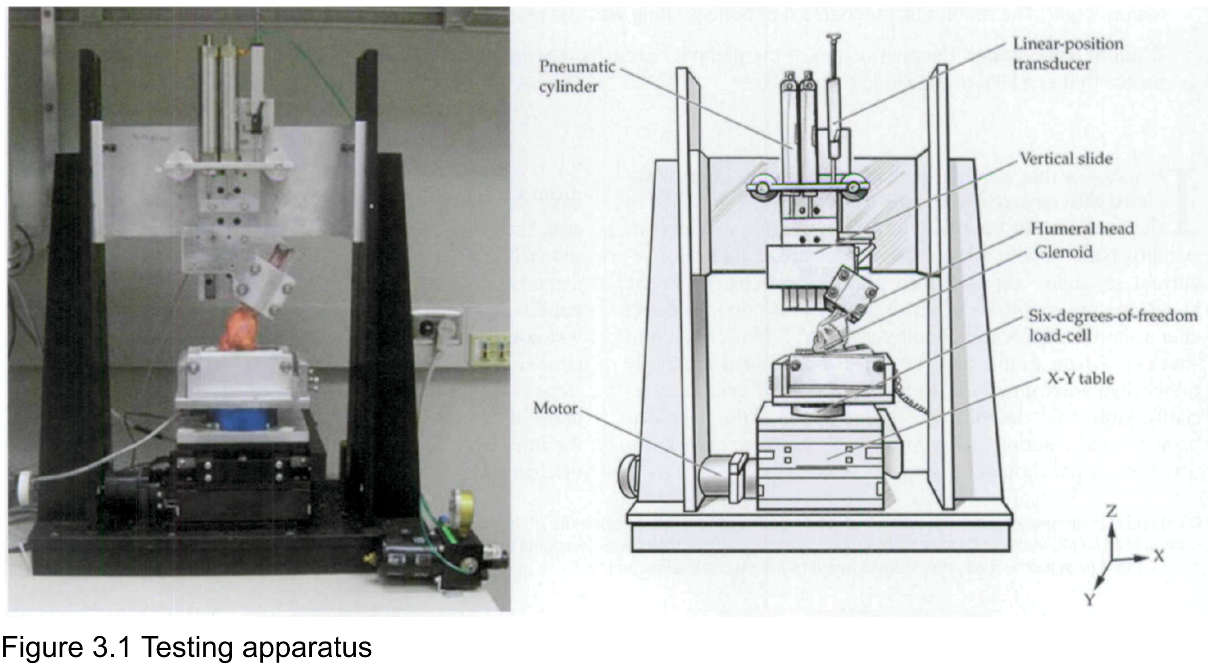


Figure 3.1 Testing apparatus

The testing apparatus as used in the experiment consisted of a load cell mounted on a programmable stepper-motor controlled x-y table. The humerus was mounted in the scapular plane to a sliding stage connected to a pneumatic cylinder at 60° of abduction and neutral rotation. This allowed free translation of the humerus in the medio-lateral (z-axis) direction while applying a constant (50 N) compressive force. Image courtesy of the Mayo Clinical biomechanical laboratory.

The reference position was determined by translating the glenoid underneath the humeral head surface until the humerus was seated at the most medial point. From the reference position, the glenoid was first translated posteriorly, resulting in anterior humeral translation, until dislocation occurred. Afterwards, the glenoid was translated from the same reference position in a postero-superior direction along a line bisecting the x- and y-axes, resulting in antero-inferior humeral head translation. Displacement and reaction forces in the x-, y- and z-directions were measured and the mean of two trials was used for data analysis.

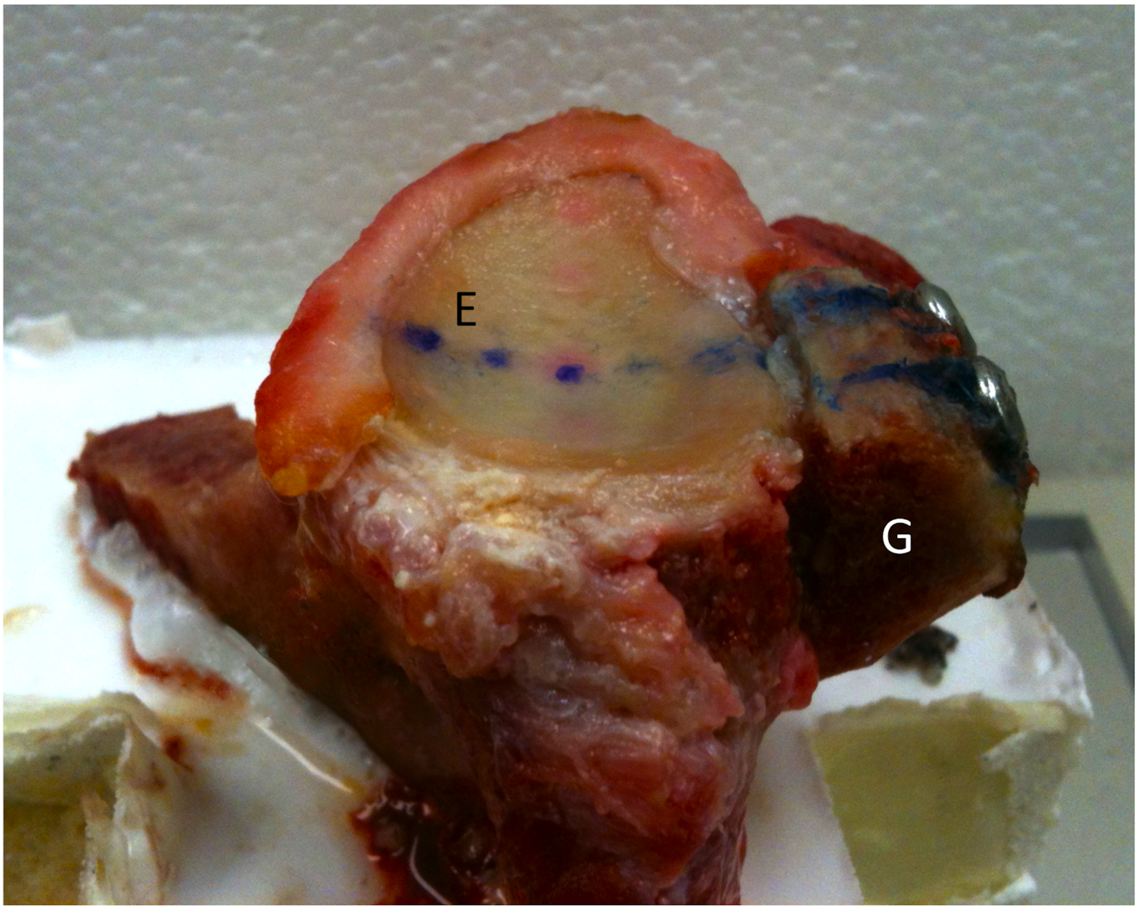


Figure 3.2. Photographic image of iliac tricortical bone graft positioned on the anterior glenoid neck using two screws. The glenoid equator is drawn on the glenoid face in blue (E), and the iliac crest graft (G) is marked in blue ink at the superior and inferior 25%.

After testing the intact glenoid, a Bankart lesion was created by elevating the labrum between the 2 o'clock and 8 o'clock positions for right shoulders and the mirrored equivalent for left shoulders. The repaired condition was tested after reattaching the labrum to the glenoid rim by means of three *2.8*-mm *titanium* suture anchors (*FASTak*; *Arthrex*, Naples, Fla., USA) at the 3, 4 and 5 o'clock positions on the anterior glenoid rim using a simple suturing technique. The bone grafted condition was tested after removing the previously elevated part of the labrum and the suture anchors. A tricortical oblique bone graft was taken from the anterior iliac crest approximately 3 cm from the anterior superior iliac spine with an oscillating saw. The graft was secured to the prepared anterior glenoid rim with two 3.5-mm AO cortical screws (Figure 3.2). The graft size (2 cm x 1.5 cm x 1 cm) was selected to match the average harvested coracoid size during Bristow-Latarjet procedures in order to avoid overestimating the effect of the free iliac bone graft (Young et al., 2013). As needed, grafts were shaped with a high-speed burr to fit the glenoid neck, but the articular (inner) side of the iliac grafts was not reshaped. The bone graft was positioned such that the concave (inner) side was flush with the glenoid cartilage, creating a smooth continuation of the articular surface (Figure 3.2). Three graft positions in the sagittal plane were tested in random order: grafts were positioned such that 50%, 75% or 100% of the graft surface area was below the glenoid equator (Figure 3.3).

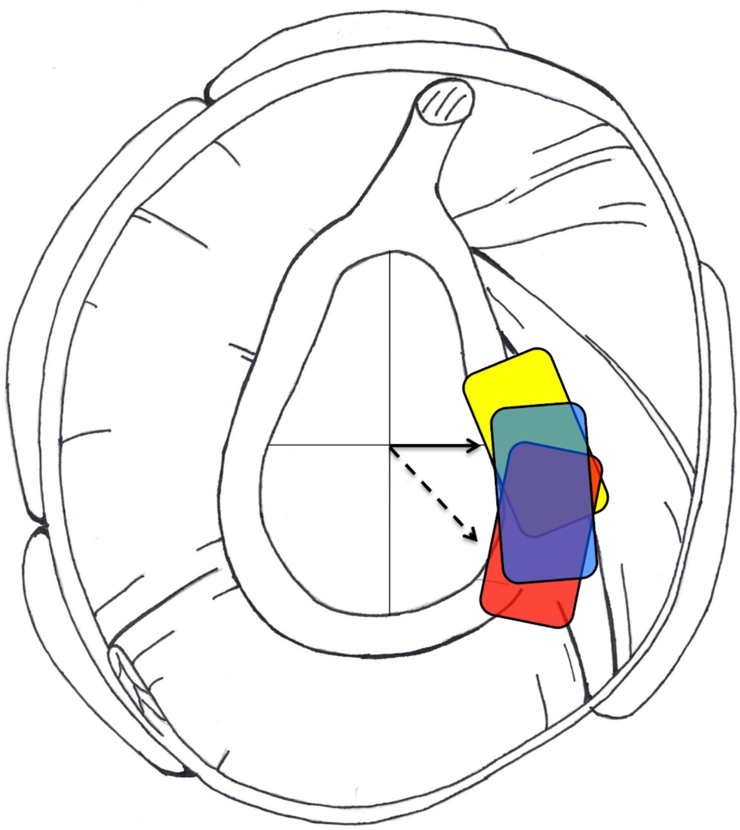


Figure 3.3. Diagram of a sagittal view of a right glenoid with labrum and rotator cuff tendons. Bone grafts depicted in three positions: 50% below equator (yellow); 75% below equator (blue) and 100% below equator (red). Full arrow indicates translation in the anterior direction, dotted arrow indicates translation in the antero-inferior direction.

The primary outcome measure was peak translational force (PF), defined as the greatest force recorded in the direction opposing translation. Absolute force values were reported instead of stability ratios, because a uniform compressive force of 50 N was applied in all conditions for this study. In addition to the instantaneous PF value, the ‘energy to dislocate’ (ETD) was calculated by numerically integrating the instantaneous translational force vs. anterior displacement of the humeral head curve from the start of the motion until the point of dislocation, as described previously (Matsuhashi et al., 2013). The point of dislocation was determined as the position where the most medial part of the humeral head reaches the most lateral part of the glenoid surface (Oosterom et al., 2003)(Walia et al., 2013).

One-way repeated-measures analysis of variance was used to compare the PF and the ETD between the intact, the Bankart lesion, labral repair and the mean bone grafted condition. Similarly, the three bone-grafted positions were compared to one another using the same statistical analysis. A Bonferroni correction was applied to the post hoc test for comparisons of more than three groups. (SPSS, IBM corp. Armonk, N.Y., USA). The level of significance α, was set at 0.05.

3.1.3.3 Results

Anterior translation of the humeral head resulted in a mean (standard deviation) PF of 14.9 N (±3.9 N) for the intact condition, 12.0 N (±5.0 N) for the Bankart lesion condition, 14.7 N (±5.5 N) for the labral repair condition and 27.3 N (±6.9 N) for the bone graft augmented condition. There was a significant decrease in PF after creation of a Bankart lesion ($p=0.048$) and a significant increase between the repaired and the grafted condition ($p=0.028$). The mean ETD was 118.4 mJ (±35.8 mJ) in the intact condition, and 87.2 mJ (±48.6 mJ) after creating the Bankart lesion, 117.0 mJ (±52.4 mJ) after labral repair and 305.1 mJ (±77.5 mJ) after bone grafting. A significant decrease in ETD was seen after the creation of a Bankart lesion ($p=0.009$) and a significant increase between the repaired and the grafted condition ($p<0.001$) (Figure 3.4, Table I). PF values for the positions 50%, 75% and 100% below the glenoid equator were 30.7 N (±8.4 N), 28.3 N (±7.3 N) and 23.0 N (±7.3 N), respectively. The 50% and the 75% position had significantly higher PF than the 100% position ($p=0.008$ and $p=0.029$) respectively. ETD showed a similar trend with respective values of 328.6 mJ (±85.3 mJ), 314.7 mJ (±73.9 mJ) and 271.9 mJ (±86.5 mJ). Comparing the three grafted conditions, grafts positioned 50% and 75% below the equator had significantly higher ETD values than grafts in the 100% below the equator position, ($p=0.029$ and ($p=0.044$) respectively (Figure 3.5 and Table II).

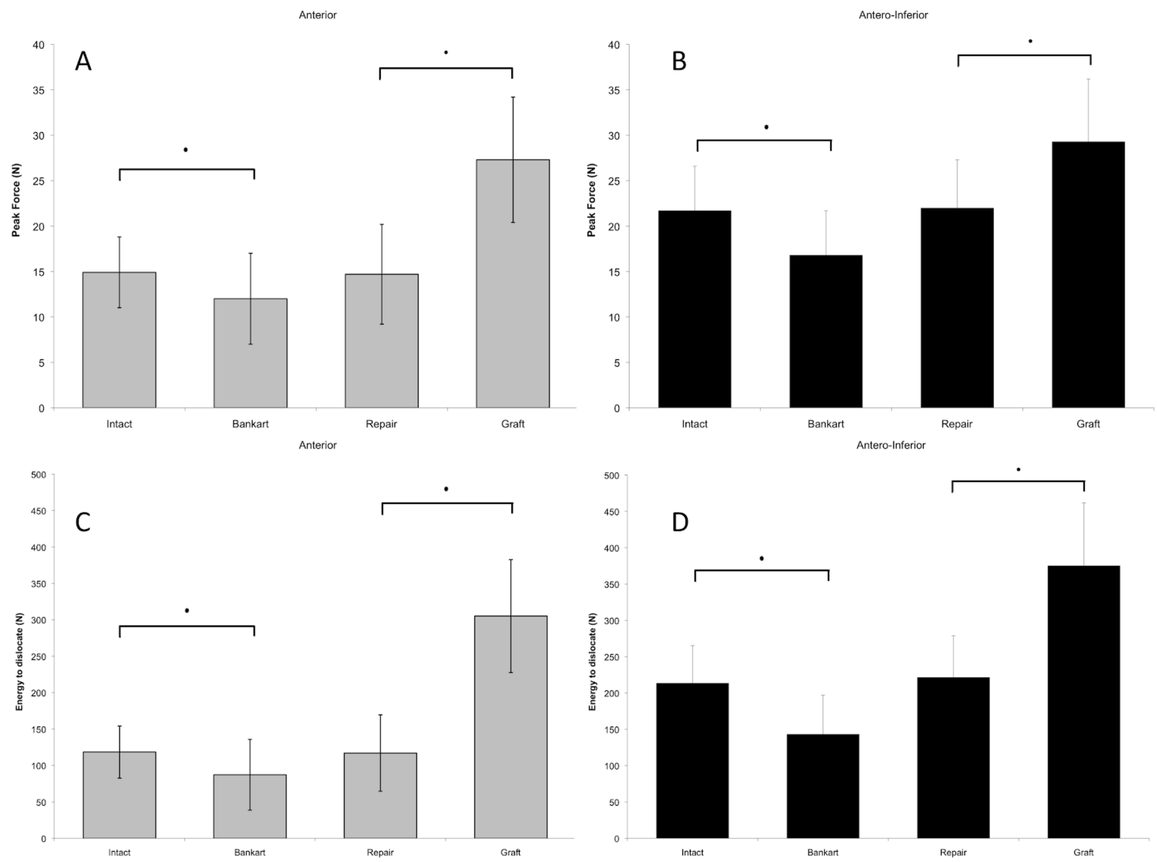


Figure 3.4. Mean peak Force (PF) and mean energy to dislocate (ETD) for the intact, Bankart lesion, labral repair and mean bone grafted condition. Anterior translation shown in grey (A-C) and antero-inferior translation shown in black (B-D). * indicates $p<0.05$. Error bars mark SD.

Antero-inferior translation of the humeral head resulted in a mean (standard deviation) PF of 21.7 N (±4.9 N) for the intact condition, 16.8 N (±4.9 N) for the Bankart lesion condition, 22.0 N (±5.3 N) for the labral repair condition and 29.3 N (±6.9 N) for the bone graft augmented condition. There was a significant decrease in PF after creation of a Bankart lesion (p=0.022) and a significant increase between the repaired and the grafted condition (p=0.024). The mean ETD was 213.6 mJ (±51.4 mJ) in the intact condition, and 143.3 mJ (±53.6 mJ) after creating the Bankart lesion, 221.5 mJ (±57.3 mJ) after labral repair and 375.3 mJ (±86.4 mJ) after bone grafting. A significant decrease in ETD was seen after the creation of a Bankart lesion (p=0.002) as well as a significant increase between the repaired and the grafted condition (p<0.001) (Figure 3.3, Table 2.1). PF values for the positions 50%, 75% and 100% below the glenoid equator were 25.6 N (±6.4 N), 30.4 N (±6.8 N) and 32.0 N (±9.0 N), respectively. Both the 100% and the 75% positions had significantly higher PF than the 50% position (p=0.031 and p=0.028, respectively). ETD showed a similar trend with respective values of 307.1 mJ (±73.4 mJ), 401.9 mJ (±94.6 mJ) and 413.3 mJ (±101.5 mJ). The 100% and 75% below the equator positions had significantly higher ETD values than grafts in the 50% below the equator position, (p=0.001 and p<0.001, respectively) (Figure 3.5 and Table 2.2). An example of the translational force vs. anterior displacement curves for all 6 conditions in both directions of translation from a representative specimen is given in Figure 3.5.

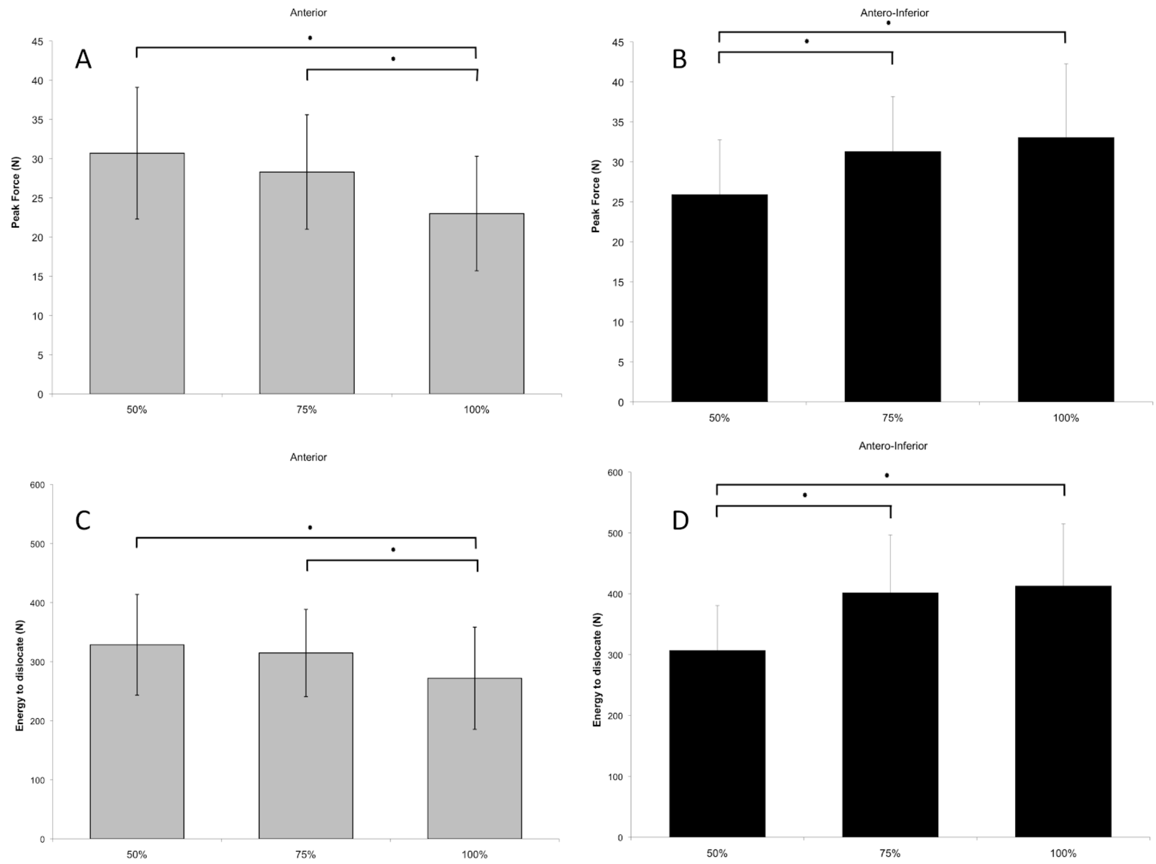


Figure 3.5. Mean peak Force (PF) and mean energy to dislocate (ETD) for the three bone grafted conditions. Anterior translation shown in grey (A-C) and antero-inferior translation shown in black (B-D). * indicates p<0.05. Error bars mark SD.

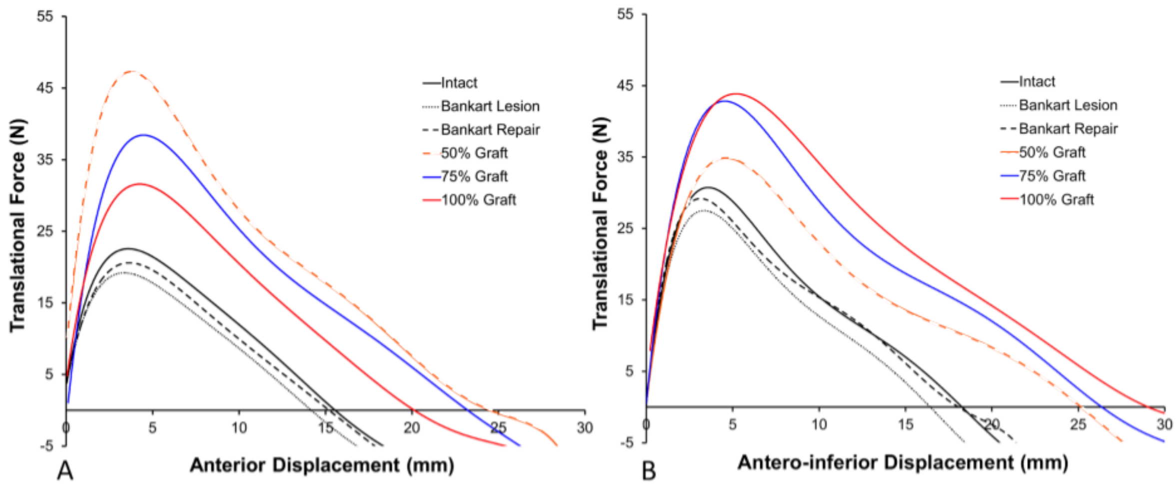


Figure 3.6. Translational force vs. anterior (A) and antero-inferior (B) displacement for all 6 conditions in a representative specimen.

3.1.3.4 Discussion

This biomechanical study confirms the positive stabilizing effect of free iliac crest graft augmentation of the intact glenoid, with a significantly higher PF and ETD in the bone grafted conditions compared to standard labral repair. Additionally, the vertical position of the graft was shown to have an important effect on stability. Bone grafts centered on the equator and 75% below the equator, displayed a significantly greater PF and ETD than grafts positioned 100% below the equator when translating in the anterior direction. Translations in the antero-inferior direction, however, revealed higher PF and ETD for grafts 100% and 75% below the equator compared to grafts in 50% position.

Despite reports of reductions in recurrence rates to as low as 0% after Bristow-Latarjet procedures as a treatment for recurrent anterior instability (Burkhart et al., 2007)(Cerciello et al., 2012)(Hovelius et al., 2012) a high incidence of complications (Butt et al., 2012)(Griesser et al., 2013)(Young and Rockwood, 1001) has generated interest in surgical alternatives. Free bone grafting of the anterior glenoid has been used to restore the glenoid articular arc with both allogeneic (Skendzel et al., 2011)(Tjoumakaris et al., 2008)(Weng et al., 2009) and autologous (Warner, 2006)(Scheibel et al., 2007)(Taverna et al., 2008)(Steffen et al., 2013) bone grafts. In the treatment of posterior instability, several authors advocate augmentation of the posterior glenoid with a free bone graft, even in the absence of glenoid erosion or dysplasia (Barbier et al., 2009)(Servien et al., 2007). In such cases, the bone graft is intended to act as an extension of the glenoid surface, rather than as an anatomic repair. Recent biomechanical studies have stressed the importance of the conjoint tendon dynamic sling effect as the primary stabilizing contributor of the Bristow-Latarjet procedure (Wellman et al., 2011)(Giles et al., 2012)(Dines et al., 2013). However, these studies all have limitations as to how closely they can recreate the sling effect. Interestingly, a recent study by Dines et al., could not demonstrate a stabilizing influence of the conjoint tendon on inferior glenohumeral translation (Dines et al., 2013). Clinical research has shown a correlation between glenoid width and risk of recurrence (Burkhart and deBeer, 2000)(Balg and Boileau, 2007)(Bernardson et al., 2014). This may be why many surgeons still strongly believe in the value of a bone graft. Additionally, in revision surgery for recurrent instability after a Bristow-Latarjet procedure, remnants of the conjoint sling are often found in situ, suggesting that the sling alone may not be sufficient to prevent instability (Lunn et al., 2008).

Free-graft bone block procedures may be less complicated than the Bristow-Latarjet procedure and recent clinical and cadaveric studies have shown their feasibility using an all-arthroscopic approach through the rotator interval (Verborgt et al., 2013). The advantages of an arthroscopic procedure include a careful exploration of intra-articular pathology, precise positioning of the graft and possibly non-violation of the subscapularis muscle (Scheibel et al., 2007)(Verborgt et al., 2013). In addition to the bony augmentation, simultaneous capsulolabral reconstruction can be performed as an all-arthroscopic procedure. Furthermore, in case of recurrence after a free bone graft procedure, conversion to a Bristow-Latarjet procedure remains possible, while revision surgery after a coracoid transfer can be technically challenging and result in inferior clinical outcomes (Lunn et al., 2008)(Young and Rockwood, 1991). Carefully selected patients could benefit from this type of bone block procedure resulting in a stronger repair than standard soft tissue reconstructions while avoiding the technical difficulties and risks associated with traditional coracoid transfer procedures. Further clinical studies are needed to confirm these advantages and to identify the ideal indication.

Positioning of the graft is shown to variably influence stability. The increase in PF and ETD between labral repair and bone grafted condition is more pronounced when translating anteriorly than antero-inferiorly. We assume this is mainly due to the increased thickness and stronger mechanical properties of the labrum found in the antero-inferior quadrant of the human glenoid (Halder et al., 2001)(Smith et al., 2008).

Although most chondrolabral lesions are found on the antero-inferior glenoid rim, superior labrum anterior and posterior (SLAP) as well as pan-labral lesions have been described (Snyder et al., 1990)(Ricchetti et al., 2012). This indicates that anterior instability may not always follow a strict antero-inferior direction. We would advise positioning the bone graft at the level of the most evident site of capsulolabral or chondrolabral detachment as observed peroperatively, assuming this location to correspond to the path of the dislocating humeral head. Future research may provide more detailed positioning guidelines when glenohumeral instability kinematics are better understood.

Graft position on the glenoid neck and congruity with the glenoid articular surface are equally critical. A proud graft reduces contact area and increases contact pressure, which is thought to correlate with the development of early osteoarthritis (Allain et al., 1998)(Hovelius et al., 2009). Medialized grafts, on the other hand, are associated with persistent instability (Hovelius et al., 2012). In this study we aimed to align the bone graft with the glenoid cartilage, creating a smooth continuation of the articular curvature. Although current surgical technique sometimes advises positioning the graft flush with the level of the subchondral bone in anticipation of fibrocartilage formation over the graft, others have suggested that positioning the graft flush with the cartilage might be optimal (Warner et al., 2006)(Steffen et al., 2013).

Despite several inherent limitations (e.g. age of donors), a cadaver model was selected for this biomechanical study because human cadaver studies yield reliable results which are more easily extrapolated to the *in vivo* condition than finite element analysis or animal studies. The biomechanical testing setup used in this study was chosen because of the proven record in analysis of concavity-compression mechanisms in the shoulder joint during midrange motion (Itoi et al., 2000)(Halder et al., 2001)(Yamamoto et al., 2010). The methodology is limited, however, in the evaluation of endrange and dynamic glenohumeral stabilizers.

3.1.3.5 Conclusion

In conclusion, this biomechanical study confirms improved anterior and antero-inferior glenohumeral stability after free iliac crest bone graft augmentation of the anterior glenoid. The results also demonstrate the importance of bone graft position in the sagittal plane, with significant differences in glenohumeral stability, depending on the direction of dislocation. Further research is needed to explore the intra-articular kinematics of the unstable shoulder as well as to determine specific clinical scenarios where patients suffering from shoulder instability may benefit from these appealing arthroscopic bone grafting procedures while avoiding the technical difficulties and risks associated with classic coracoid transfers.

		Intact	**Bankart Lesion**	**Labral repair**	**Bone Graft**
Anterior	PF (N)	14.9 (3.9)	12.0 (5.0)	14.7 (5.5)	27.3 (6.9)
	ETD (mJ)	118.4 (35.8)	87.2 (48.6)	117.0 (52.4)	305.1 (77.5)
Antero-inferior	PF (N)	21.7 (4.9)	16.8 (4.9)	22.0 (5.3)	29.3 (6.9)
	ETD (mJ)	213.6 (51.4)	143.3 (53.6)	221.5 (57.3)	375.3 (86.4)

PF; peak force, ETD; energy to dislocate.

Table 2.1 PF and ETD for the intact, Bankart lesion, labral repair and mean bone grafted condition in anterior and antero-inferior translation. Values given as mean and (SD).

		50% under equator	75% under equator	100% under equator
Anterior	PF (N)	30.7 (8.4)	28.3 (7.3)	23.0 (7.3)
	ETD (mJ)	328.6 (85.3)	314.7 (73.9)	271.9 (86.5)
Antero-inferior	PF (N)	25.6 (6.4)	30.4 (6.8)	32.0 (9.0)
	ETD (mJ)	307.1 (73.4)	401.9 (94.6)	413.3 (101.5)

PF; peak force, ETD; energy to dislocate.

Table 2.2 PF and ETD for the three bone-grafted conditions (50%, 75% and 100% below the equator) in anterior and antero-inferior translation. Values given as mean and (SD).

3.1.4 Bipolar Bone Loss

Glenoid bone loss and Hill-Sachs lesions are known to coincide in recurrent dislocators (Griffith et al., 2008)(Nakagawa et al., 2015). However, biomechanical literature on this topic is limited. A cadaveric study by Arciero and colleagues confirmed that bipolar bone loss has a negative additive effect on glenohumeral stability. A small (8%) glenoid defect was sufficient to significantly destabilize the joint in the presence of a medium-sized Hill-Sachs lesion, and small Hill-Sachs lesion sufficed to compromise a bankart repair in the presence of 15% glenoid bone loss (Arciero et al. 2015). A study by Patel and colleagues investigated the glenohumeral interactions in shoulders with incremental glenoid and humeral bone loss after a Latarjet procedure. The shoulders, devoid of soft-tissues, were translated under a standard compressive force until dislocation occurred in several conditions of abduction, rotation and bone loss. In the higher degrees of abduction (60°) and external rotation (80°), the Latarjet procedure was only partially able to restore the amount of translation before dislocation in the presence of a large Hill-Sachs lesion (31-44%). Compared to the native condition, the Latarjet procedure offered only 65% and 30% of the normalized translational distance before dislocation (Patel et al., 2016). Hartzler et al., compared cadaveric shoulders with 15% glenoid bone loss and either 15% (on-track) or 30% (off-track) humeral bone loss after Bankart repair or Bankart repair and remplissage. The authors demonstrated the inability of Bankart repair to stabilize all off-track lesions at the endrange of motion. The addition of a remplissage prevented engagement yet increased stiffness in mid- and endrange to supraphysiological levels (Hartzler et al., 2016). Cadaveric studies on this topic are relatively scarce due to the limitations of modelling bipolar lesions, treatment strategies and instability in anatomic specimen in a validated and realistic fashion.

3.2 Numerical Biomechanical Studies

Digital, also called numerical or virtual glenohumeral instability models have been put forth as an alternative to the complicated, time-consuming, expensive and possibly unreliable cadaveric experiments. Walia and colleagues developed a numerical finite element model simulating the translation between a humeral head and a glenoid articular surface under compressive load. The model allowed for two angles of humerothoracic abduction and various humeral rotational angles. The results compared well with the existing cadaveric literature on stability performed by Itoi using the Mayo Clinic testing apparatus (Itoi et al., 2000). The authors reported a greater destabilizing effect of bipolar lesions compared to similar but isolated glenoid and humeral injuries, depending on the degree of abduction and rotation (Walia et al., 2013). In a follow-up paper, some of the same authors investigated the role of bipolar bone lesions on range of motion and found that while glenoid lesions influenced stability, and more precisely distance to dislocation (DTD) throughout the range of motion, the humeral head lesions only came into play at greater degrees of abduction and external rotation (Walia et al., 2015). Finite element models have many potential advantages, yet are often held back by the obligatory external validation requirements.

Our experiences with the biomechanical experiments on free bone grafting in intact glenoids led to a second technical paper which aimed to mathematically predict stability and kinematics from articular surface properties only (Willemot et al., 2015). The short communication paper ‘Shoulder stability as a cam-follower mechanism” is presented in full below. Subsequent work done at the Mayo Clinic biomechanical laboratory used this methodology to evaluate the so-called bony shoulder stability angle (BSSR) which was introduced by Moroder and colleagues in 2015 (Moroder et al., 2015). The BSSR derives the peak translational force from simple Pythagorean trigonomics. The calculation only requires the depth and curvature of the glenoid surface which can easily be measured on axial CT images. The formula was initially used to demonstrate inherent flattening of the glenoid surface of traumatic and atraumatic recurrent dislocators (Moroder et al., 2015). The BSSR was first validated in a finite element study which accompanied the aforementioned paper and later physically validated using the Mayo Clinic apparatus as a continuation of our preliminary work. Importantly, the BSSR does not take into account the importance of DTD when evaluating glenohumeral stability (Ernstbrunner et al., 2016). Selective evaluation of peak translational force without consideration for DTD may lead to the false assumption of overall stability, when only macro-stability is assured. The BSSR is an interesting and simple tool for the assessment of constraint, but fails to accurately reflect the finer elements of glenohumeral contact such as congruence.

In general, finite element models have proven difficult in complex biomechanical systems, and so far no computer simulations have been presented with the ability to accurately predict glenohumeral interactions during instability with the inclusion of capsuloligamentous en muscular structures. Other imaging-based models, such as the glenoid track concept explained in Chapter 2., have shown greater promise and clinical applicability in this area (Yamamoto et al., 2007).

3.2.1 Introduction

The shoulder joint exhibits ball-and-socket-like kinematics with a limited degree of humeral head (HH) translation (Graichen et al., 2000; Howell and Galinat, 1989; Kelkar et al., 2001; Poppen and Walker, 1975). Shoulder instability is defined as the inability to maintain the HH centered within the glenoid fossa (Graichen et al., 2000; Howell and Galinat, 1989; Lippitt et al., 1993; Matsen et al., 1991; Poppen and Walker, 1975). Biomechanically speaking, instability is a condition defined by the inability of a joint to return to its original position after perturbation (Kelkar et al., 2001; Leipholz, 1987). Clinically, the perturbed configuration corresponds to a dislocation, while instability refers to a larger than acceptable translation occurring during force exertion (Veeger and van der Helm, 2007).

In midrange shoulder joint motion, concavity-compression is the most important mechanism of shoulder joint stability (Lazarus et al., 1996; Lippitt et al., 1993). Concavity-compression is the mechanism in which the convex humeral head is stabilized against translating forces by the concave glenoid fossa. The stability is related to the magnitude of the compression (Fukuda et al., 1988) and the constraint offered by the glenoid concavity (Anglin et al., 2000). Traditional experimental studies investigating shoulder stability, have either measured translational force during driven displacement (Favre et al., 2011; Halder et al., 2001; Itoi et al., 2000; Karduna et al., 1997; Kikuchi et al., 2008; Tammachote et al., 2007; Yamamoto et al., 2009) or have measured displacement after applying a predetermined translational force (Bryce et al., 2010; Elkinson et al., 2012; Giles et al., 2011; Mihata et al., 2012; Peltier et al., 2012; Schulze-Borges et al., 2013; Sekiya et al., 2012; 2009; Wellmann et al., 2011a; 2011b; 2008). Oosterom et al. published a mathematical model allowing prediction of the "translational stiffness" of the shoulder joint after arthroplasty (Oosterom et al., 2003). In the paper, the authors define a mathematical model for glenohumeral prostheses that defines translation force over 3 distinct "positions" and 2 “regions” of instability (Figure 3.7). Briefly, from the centered position (position 1) the HH slides (region 2) until the sliding angle φ_1 is equal to the constraint angle θ at the glenoid rim (position 3). Further sliding beyond position 3 (region 4) is termed subluxation, until the subluxation angle φ_2 is equal to θ, at which point the HH is truly dislocated (position 5). The total travel along the direction of translation until position 5 is reached is commonly referred to as "distance to dislocation".

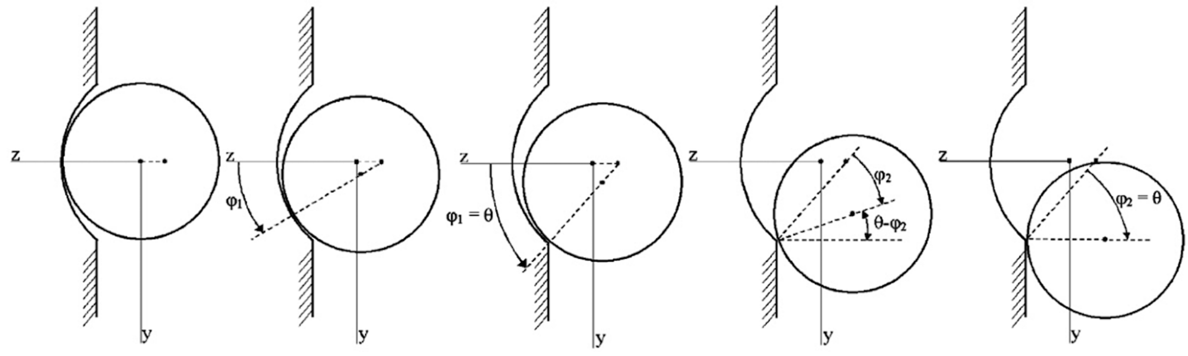


Figure 3.7
Regions and positions of glenhumeral motion decribed by Oosterom et al. θ = glenoid component constraint angle, calculated by glenoid chord / 2 radius of curvature of the glenoid, Φ1 = instantaneous angle between the z-axis, origin of the glenoid sphere and the instantaneous center of HH, Φ2 = = instantaneous angle between the origin of the glenoid sphere, the glenoid rim and the instantaneous center of HH .
Used with permission of Elsevier. Previously published in Oosterom, R., Herder, J.L., van der Helm, F.C.T., Swieszkowski, W., Bersee, H.E.N., 2003. Translational stiffness of the replaced shoulder joint. Journal of Biomechanics 36, 1897–1907.

Recently, much attention has been given to the role of bone loss in glenohumeral instability. Clinical and experimental data suggests that both glenoid and humeral bone loss significantly increase the risk of recurrent instability (Kaar et al., 2010; Walia et al., 2012). On a theoretical level, the glenoid track concept illustrates the mechanism by which bone loss on either part of the joint interferes with glenohumeral stability due to alterations in articular geometry. (Trivedi et al., 2014; Yamamoto et al., 2007)

Our hypothesis was that the kinetic and kinematic interactions within the glenohumeral joint during simulated experimental dislocation (translation under compression), can be accurately defined using machine design principles, modeling the glenohumeral joint as a cam-follower mechanism. From this perspective, the HH functions as the follower translating over the cam-like glenoid surface. Thus, humeral head trajectory and translational forces could be predicted using only contact surface geometry and compressive forces as function inputs. In comparison to previous work by Oosterom et al. (Oosterom et al., 2003), our model derived equations valid for non-circular shapes, making the concept applicable to a variety of clinical purposes such as the study of native glenohumeral anatomy and the influence of bone defects on joint stability. We illustrate this new method of determining glenohumeral instability and characterize the accuracy of the approach by physically testing an idealized shoulder model and comparing data to the output of 2D mathematical models. We also briefly evaluate the robustness of the model by examining interactions with both small and large HH's under different compressive loads.

Materials and Methods

Experimental set-up

An idealized physical model of a ball and socket, approximating a humeral head and a glenoid, was fabricated with careful control over geometric parameters. The glenoid was molded using semi-rigid urethane casting resin (Smooth-Cast 65®D, Smooth-On, Inc, Easton, PA,USA) and a 80-mm diameter sphere as a mold pattern to form a concave articulating surface, resulting in an axisymmetric cup 39.6 mm in radius and 17.5 mm deep with a constraint angle, θ, of 56°. Two different HH sizes were created using off-the-shelf polyoxymethelene spheres, one small (25.4-mm radius) and the other large (38.1-mm radius). The heads were fitted onto a 175-mm long polycarbonate rod simulating the humeral shaft. The marked difference in humeral head sizes was deliberately chosen to accentuate the differences in experimental test results. Although deviating head sizes limits the anatomical accuracy of the glenohumeral model, they do not compromise the aim of this paper to illustrate a mathematical concept.

These HH and glenoid surrogates were mounted onto the custom-built four-axis electromechanical set-up, described earlier in the cadaver experiments to assess midrange glenohumeral stability (Figure 3.1)(Halder et al., 2001; Itoi et al., 2000; Matsuhashi et al., 2013; Yamamoto et al., 2009; 2010; 2012). In the first experiment the stability of the small and large HH models were evaluated under a 50-N compressive force applied during translation. In the second experiment the small HH was translated under compressive loads of 30 N, 60 N and 90 N, consecutively. Silicone lubricant was sprayed on the articulating surfaces before each test. Translation was initiated from a position 50 mm ahead of the most medial (reference) point and progressed under displacement control at 2 mm/sec for 100 mm along the y-axis. Position and force data collection was initiated after the HH crossed the reference point.

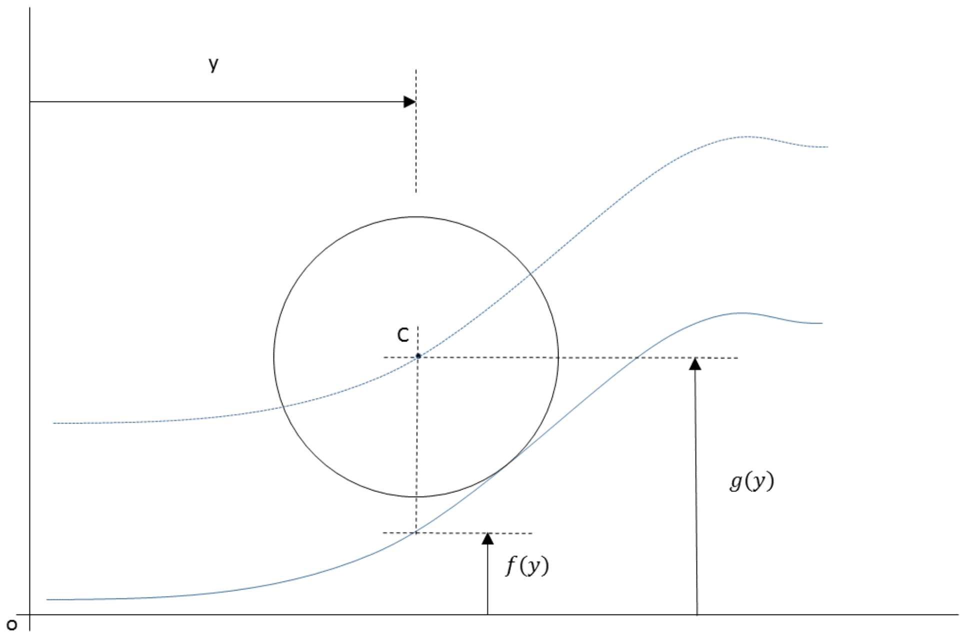


Figure 3.8.
Description of the HH path over a cam-like surface. f(y) : function defining cam surface,

g(y) : function defining follower path, C: center of the HH, modeled as a follower.

Mathematical 2D cam-follower model

In this mathematical approach to analytically assess joint stability, the glenohumeral joint was modeled with a spherical follower emulating the HH and a linear translating cam as glenoid, as shown in 2D representation in Figure 3.8. The follower was assumed to be circular with a radius, *r*. The surface of the cam is represented as a function $f(y)$. The trajectory of the follower is similarly represented by another function, $g(y)$. The instantaneous point of contact between cam and follower is designated r* as shown in figure 3.9.

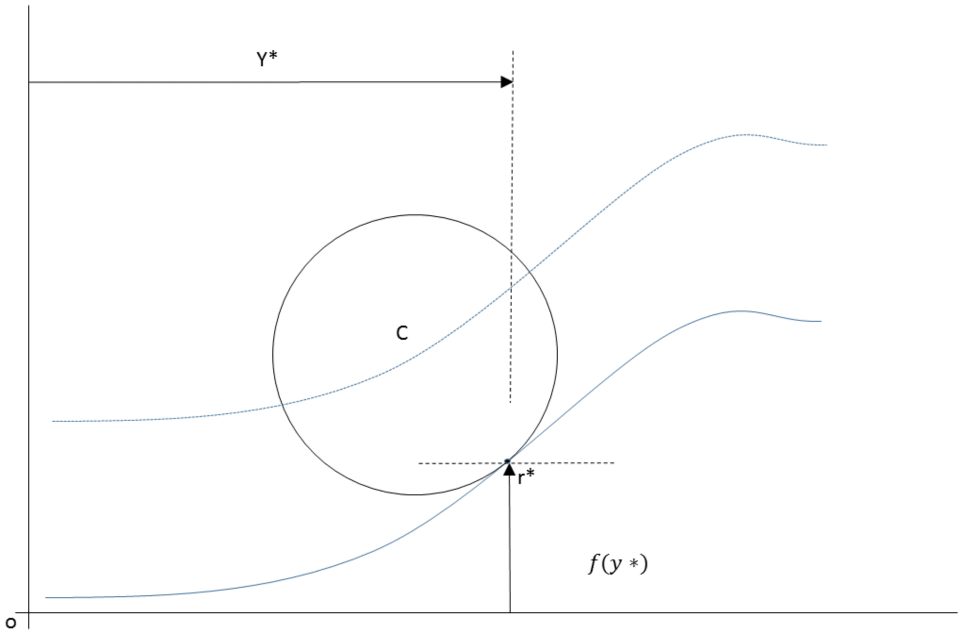


Figure 3.9
The instantaneous point of contact between the cam and follower is designated as r*.

The position of the cam center (C) can be found by simple vector addition of position vectors, one between follower center and the instantaneous contact point, $\bar{r}*_{C/H}$, and the second defining the contact point relative to the most medial position reference, $\bar{r}*$, (Equation 1)(Figure 3.10).

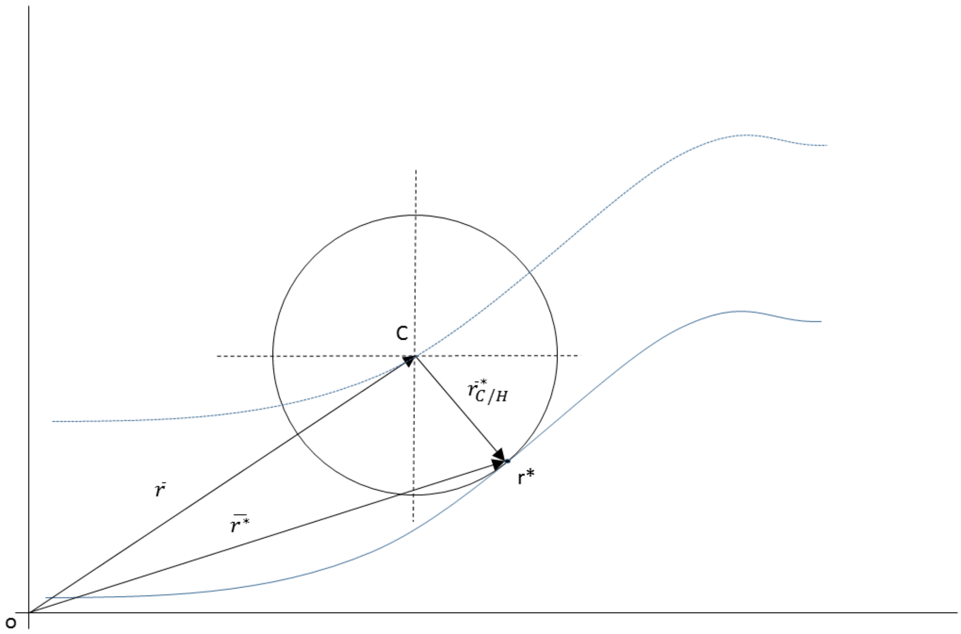


Figure 3.10

Vector defining the position of C is designated $\bar{r}$, the position of r* is designated $\bar{r}*$, and designating the position of C in relation to r* is denoted $\bar{r}*_{C/H}$.

The position vectors can be expressed in cartesian coordinates with unit vectors, i and j (Equations 2 and 3). Since $\bar{r}*_{C/H}$ must be perpendicular to a line tangent to f(y) at the point of contact, the angle between the vertical axis and $\bar{r}*_{C/H}$ is equal to the angle between the line tangent to f(y) at the point of contact, angle (*β(y)) (Figure 3.11).*

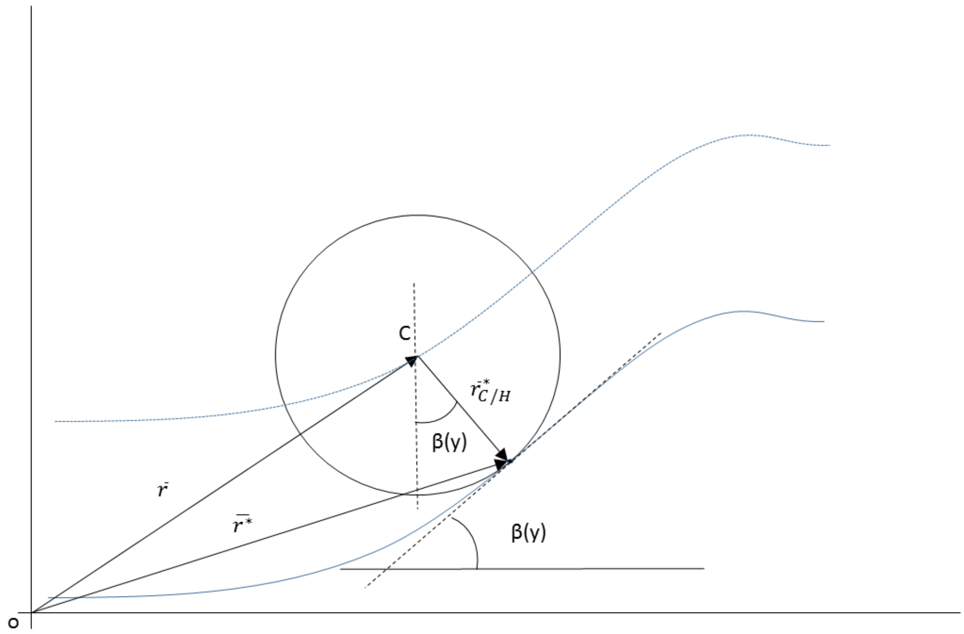


Figure 3.11

The angle *β(y)* between the vertical and $\bar{r}*_{C/H}$ is equal to the arctangent of the slope of f(y) at the point of contact because $\bar{r}*_{C/H}$ is always perpendicular to the tangent of f(y) at r*.

This permits $\bar{r}*_{C/H}$ to be expressed as the vector sum with components in terms of parameters previously established. (Equation 4)(Figure 3.12). Resolving the original positional vector sum (Equation 1) with the unit vectors (Equations 2 and 3) and the vector sum of $\bar{r}*_{C/H}$ based on the tangent angle (Equation 4) leads to the Equation 5. Creating separate equations for each unit vectors in the solution leads to the expressions for *y* and $g(y)$ relative to the contact point (Equations 6 and 7).

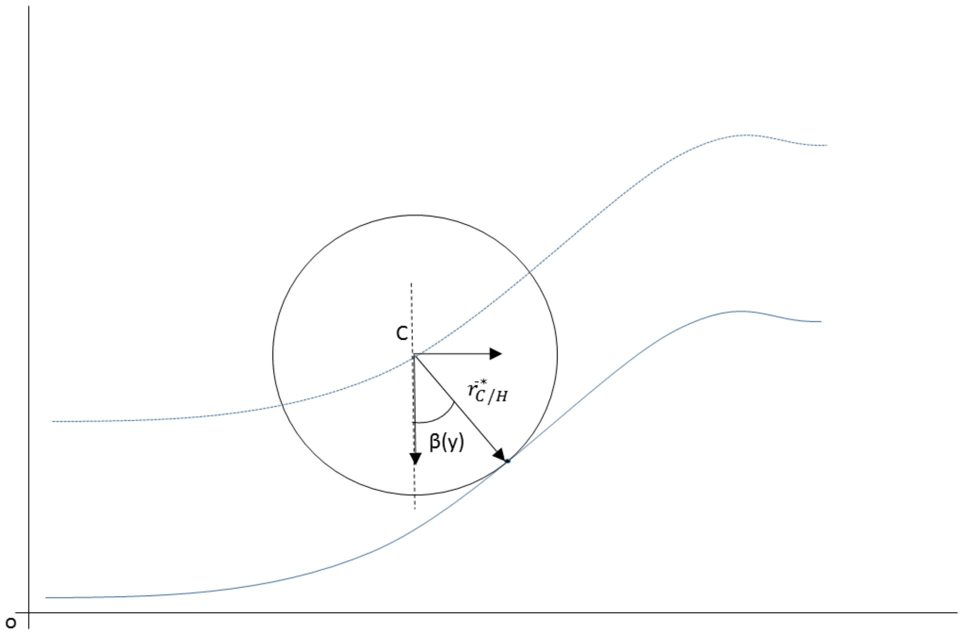


Figure 3.12

Vector sum of $\bar{r}^*_{C/H}$ orthogonal constituent vectors.

The instantaneous slope of the cam profile can be calculated differentiating the cam profile, $\frac{d}{dy}f(y)$ (Equation 8). Finally, substituting the expression for tangent angle, *β,* and applying a shift in *y* using the relationship in Equation 2, a general solution for the follower, or HH, path is obtained (Equation 9). Similar expressions could be developed for an irregularly shaped humeral head with surface contour *h(y)*; however, simple numerical methods would likely be required to obtain a solution. If frictionless contact between the HH and glenoid surface is assumed, the force required to translate the HH, $F_Y(y)$, for a constant axial load, F_Z, can be determined from equations of static equilibrium (Equation 10). Results are reported as the ratio between $F_Y(y)$ and F_Z to allow for extrapolation to values commonly reported in the literature.

$\bar{r} = \bar{r}^* - \bar{r}^*_{C/H}$ Equation 1

$\bar{r} = y\bar{\imath} + g(y)\bar{\jmath}$

$\bar{r}^* = y^*\bar{\imath} + f(y^*)\bar{\jmath}$ Equations 2 and 3

$\bar{r}^*_{C/H} = r\sin(\beta\,(y^*))\bar{\imath} - r\cos(\beta\,(y^*))\bar{\jmath}$ Equation 4

$$y\bar{\imath} + g(y)\bar{\jmath} = (y^*\bar{\imath} + f(y^*)\bar{\jmath}) - (r\sin(\beta(y^*))\bar{\imath} - r\cos(\beta(y^*))\bar{\jmath})$$

Equation 5

$$y = y^* - r \cdot \sin(\beta(y^*)) \qquad g(y) = f(y^*) + r\cos(\theta(y^*))$$ Equation 6 and 7

$$\theta(y) = \arctan\left(\frac{d}{dy} f(y)\right)$$ Equation 8

$$g(y - r \cdot \sin(\beta(y))) = f(y) + r \cdot \cos(\beta(y))$$ Equation 9

$$F_Y(y - r \cdot \sin(\beta(y))) = F_Z \cdot \tan(\beta(y))$$ Equation 10

If the cam path is circular within region 2, as described previously by Oosterom and detailed in Figure 3.6 (left), the equation for translation force (Equation 11) can be greatly simplified, with the center moving along a circular path of radius (ρ - r).

$$F_y(y) = Fz\frac{y}{\sqrt{(\rho - r)^2 - y^2}}$$ Equation 11

After reaching articular position 3 (Figure 3.7), the follower center is described by another circular path with radius of curvature, r (Equation 12). As detailed in Figure 3.13 ≥(right), translation force for region 4 can be expressed as in Equation 13: (equation adapted from Oosterom et al.)

$$g(y) = -\sqrt{r^2 - (y - l)^2} + (d - r)$$ Equation 12 (l=½ of glenoid width)

$$Fy(y) = Fz \cdot \sqrt{\frac{(r \cdot \sin\theta - (y - (\rho - r) \cdot \sin\theta))^2}{r^2 - (r \cdot \sin\theta - (y - (\rho - r) \cdot \sin\theta))^2}}$$ Equation 13

With these simplified definitions for the HH force, profiles were generated simulating each of the conditions modeled and physically tested.

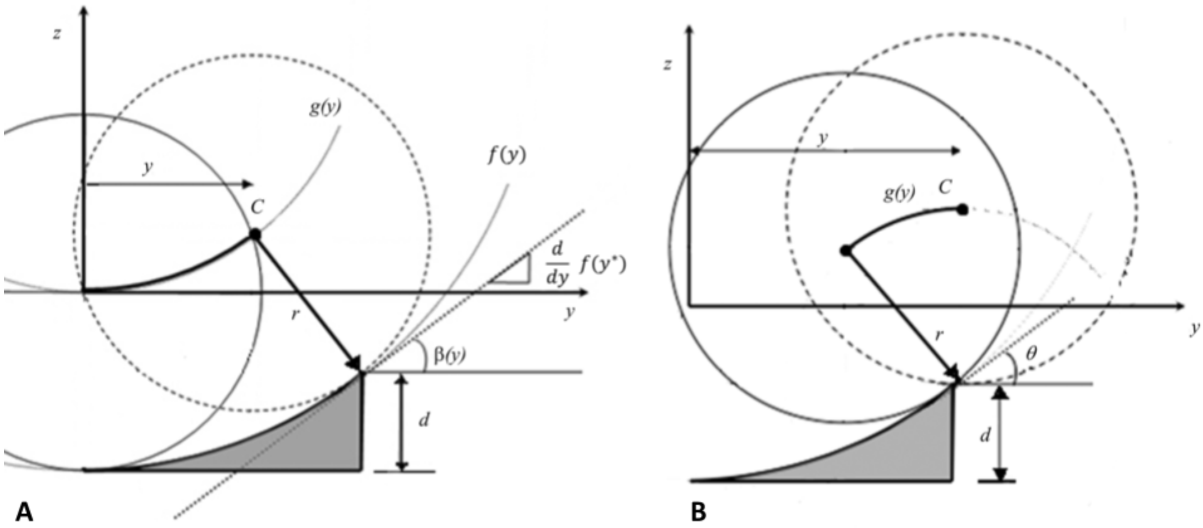


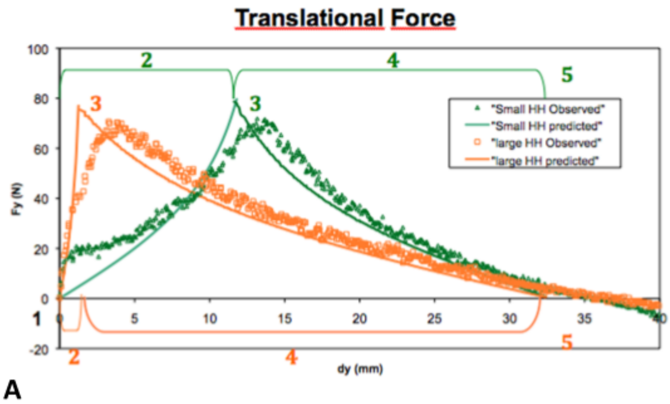
Figure 3.13
Schematic representation of the glenohumeral joint during experimental translation. Left and right drawings represent translation from position 1 - 3 and 3 - 5, respectively.

Data Analysis

The fit of the predicted translation force and lateral displacement data to the experimental data were characterized by calculating the coefficient of determination, r^2 , with an r^2 of 1 indicating perfect representation of the data with the model. The criterion for a good fit in this study was set at $r^2 \geq 0.85$.

Results

A plot of predicted and measured force and displacement data over the different regions is shown in Figure 3.14. The plots exhibit the characteristic articular positions and regions. As expected, peak force is unaltered when constraint and compressive load remain the same, regardless of HH size. However, the y-distance traveled to reach the peak force (subluxation distance (Oosterom et al., 2003)) increases as mismatch between glenoid and humeral radius becomes greater. Comparison of translational forces (y-direction) between experimental and mathematical approaches for the small HH (with a compression force of 50 N) resulted in an r^2 of 0.88. The same comparison for the large HH resulted in an r^2 of 0.89.. For similar comparisons of the lateral displacement (z-direction), r^2 was 0.99 and 0.98 for the small and large HH, respectively. A comparison of the experimental and mathematical translational force for different compressive loads is shown in Figure 5. Coefficients of determination for 30-N, 60-N and 90-N compressive loads were 0.90, 0.82 and 0.89, respectively



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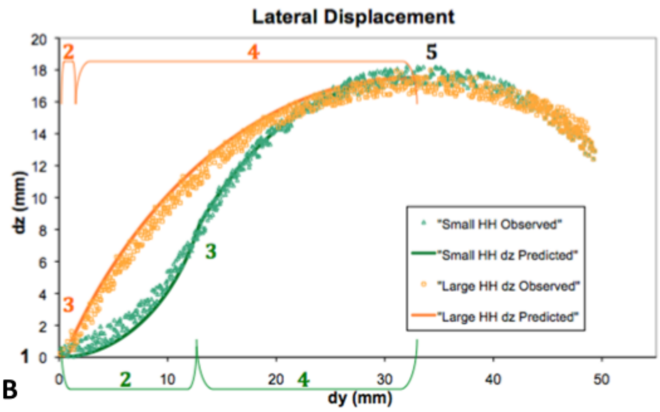

B

Figure 3.14
Comparison of measured and predicted a) stability ratio and b) lateral displacement under 50-N compressive load.

Discussion

Constraint and conformity

The aim of this paper was to derive a general equation based on cam-follower mechanics and validate the accuracy of this approach for a simplified glenohumeral model. As demonstrated above, the model performed well and the generated data agreed well with the observational data. Analyzing spherical objects simplified the mathematical equations, but non-spherical surfaces can be analyzed in the same fashion provided their surfaces can be described as a function (or series of functions). The derivation presented in this paper has been generalized to apply to any such function describing the surface contour. By testing two HH diameters with the same glenoid cup, we created a model with constant constraint but different conformity (HH radial mismatch). As defined by Anglin et al. (Anglin et al., 2000) constraint is determined by the maximum slope at the glenoid rim, which, in a 2D perspective, is in turn dependent on the sector angle enclosing the glenoid (θ). As demonstrated in our first experiment, changes in conformity yield predictable results in terms of force vs. displacement curves in our cam-follower model. The HH and glenoid dimensions were not selected to represent anthropometric glenohumeral proportions but, rather, to demonstrate the robustness of the mathematical model regarding variable conformity. Variance in constraint was not included in this study in the interest of brevity.

An assumption of this mathematical approach is that surfaces are rigid and frictionless. Mismatch between predicted and observed values can at least partly be explained by the elasticity and friction present in our physical model. Discrepancies in the translational force curves are most noticeable at two locations. The first occurs during the first millimeters of translation from the most medial position, and the second occurs when peak force is reached. The deviation is most likely due to the relatively low stiffness of the material from which the glenoid was made. The data in Figure 3.15 indicates a higher degree of mismatch under increasing loads, which supports this theory. When analyzing highly deformable surfaces with friction and more complicated geometry, finite element analysis may be a more practical tool for modeling joint stability. However, we expect this mathematical model to increase the understanding of cadaveric experimental results and potentially reduce future cadaver testing for the evaluation of conditions that influence concavity-compression shoulder stability. Moreover, this universal approach may be applied to other ball-and-socket articulations subject to instability such as the hip, radiocapitellar joint or even condylar (ellipsoidal) joints such as the wrist and metacarpophalangeal articulations.

There are several limitations to this study. Inclusion of diverging material stiffness and lubrication conditions may have established the impact of native articular cartilage and labral tissue deformability more clearly. Secondly, simplifying interactions between 3D objects to 2D contact models is not fully representative of the joint behavior, yet the direction of follower travel was constrained either externally, effectively reducing this to a 2D problem. Additionally, visual appreciation of the proximity between cam and follower during the experiments demonstrated that all interactions between surfaces occurred within the plane of travel.

It is our conviction that the use of simple mathematical models such as this one will aid in the design and comprehension of experiments in stability research and may avoid unnecessary depletion of cadaveric resources.

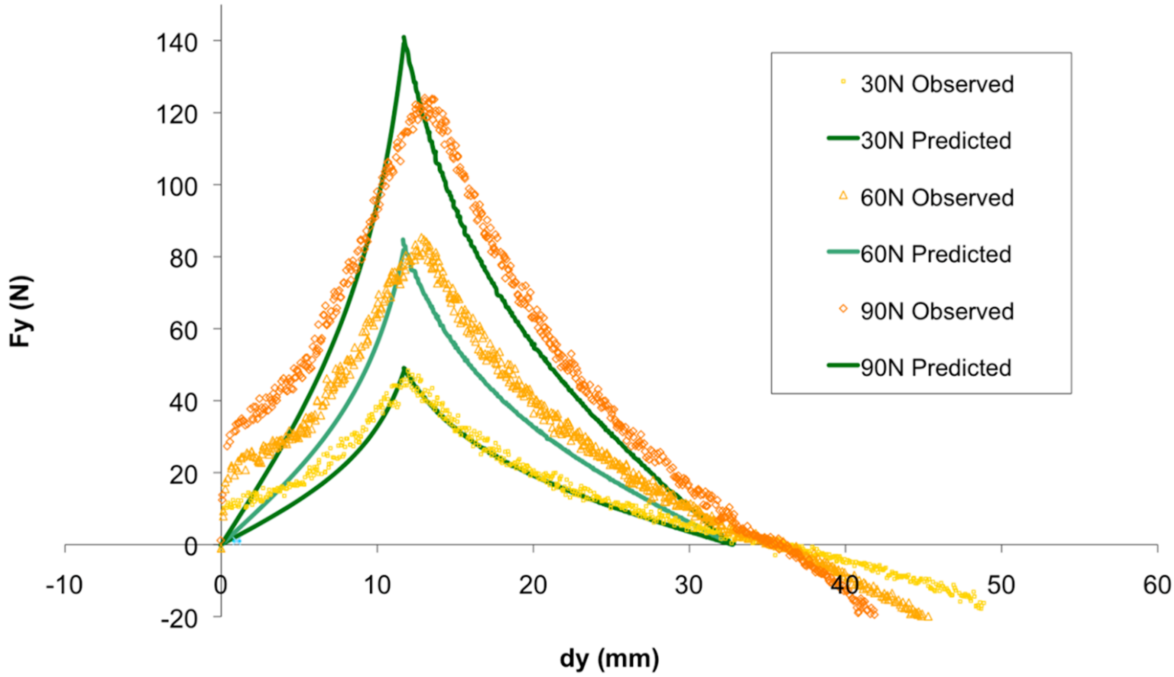

Figure 3.15
Comparison of measured and predicted translation forces for compressive loads of 30 N, 60 N, and 90 N.

3.3 In-vivo Biomechanical Studies

3.3.1 Normal in-vivo Shoulder Biomechanics

A major obstacle in *in-vitro* biomechanical shoulder studies is the complexity of dynamic *in-vivo* glenohumeral mechanics and kinematics. The uncertainty regarding the contribution of the diverse muscles, ligaments, and articular constraints inexorably leads to difficulties in the experimental modelling of shoulder motion and stability in cadaveric or abstract techniques. One solution has been to circumvent the problem, by directly investigating the biomechanics in living human subjects. A persistent mystery in the field of shoulder biomechanics is whether the joint actually behaves as a ball-and-socket articulation or not. For a long time, researchers have investigated if glenohumeral translations occur in the coronal and sagittal planes during physiologic shoulder motion. Answering this question correctly is a prerequisite to further research into the pathological translations present in glenohumeral instability.

Poppen and Walker investigated glenohumeral translation in healthy individuals during intermittent abduction using standard radiographs (Poppen and Walker, 1975). Yet static 2D imaging fails to capture the complexity of the 6 degrees of freedom in dynamic shoulder motion. Early attempts of 3D imaging techniques with open MRI and biplane fluoroscopy were interesting, yet largely limited to static images (Baeyens et al., 2001)(Graichen et al., 2000)(Paletta et al., 1997). Conventional motion tracking systems based on optical or magnetic skin markers have proven too susceptible to skin movement artifacts and are therefore not applicable for the measurement of submillimeter glenohumeral translations (Ludewig and Cook, 2002). Alternatively, the sensors can be fastened to bone pins, significantly increasing the precision. However, intraosseous fixation reduces the applicability due to concerns about the invasiveness of the procedure (Mclure et al., 2001).

More recently, dynamic biplane fluoroscopy methods have been refined. Bey and colleagues matched 3D CT models of patients' scapulae and humeri to 2D biplane fluoroscopic images in order to dynamically recreate the 3D positions of each bone in space. The authors reported a superior-inferior translation of 2.6 mm during abduction and anterior-posterior translation of 2.1 mm during external rotation (Bey et al., 2008). Nishinaka used a similar protocol in healthy individuals and found a mean of 1.7 mm of superior migration from an inferior position to the glenoid center during abduction (Nishinaka et al., 2008). Massimini and colleagues reported their results combining MRI images with biplane fluoroscopy. The authors found a range of 6 mm anterior-posterior motion and 2.5 mm superior-inferior path during abduction in young and healthy individuals. In maximum external rotation, anterior translation of up to 4.7 mm was observed, while maximum internal rotation shifted the humeral head back to a position 1.2 mm posterior to the glenoid center (Massimini et al., 2012). Open MRI investigations have typically revealed anterior translations ranging from 1-2 mm. However, these studies are typically hampered by the semi-static nature of the experiments (Cereatti et al., 2014)(Von-Eisenhart-Rothe et al., 2010). A recent study combining motion trackers and intracortical pins found anterior translations of up to 3.4 and 9.4 mm in the two study participants during range of motion exercises and sports activities (Dal Maso et al., 2015).

Care should be taken when comparing such results, because variations may occur as a result of different techniques in the calculation of translation (Matsuki et al., 2016). Nevertheless, the findings further cement the notion that the glenohumeral joint does not entirely behave as a ball-and-socket articulation. This understanding is crucial in our interpretation of measurements found in unstable shoulders.

3.3.2 In-vivo Shoulder Instability Pathomechanics

The recognition of pathological motion at the glenohumeral interface during dynamic exercise would be of great interest in the guidance of conservative and surgical therapy for shoulder instability. Older studies using radiography and skin markers for motion tracking will not be discussed due to the proven inability of such methods to measure submillimeter and subdegree changes (Ludewig and Cook, 2002). Kim and colleagues investigated glenohumeral translation in patients after primary dislocation using monoplane 3D to 2D matching techniques as described earlier. Analogous to Bey, the authors reported an initial superior humeral head translation, followed by a gradual return during abduction. This is believed to be the result of rotator cuff activation stabilizing the humeral head after the initial upwards motion caused by the deltoid muscle contraction. The authors also reported an increased anterior translation of 2.29 mm in the dislocated shoulders compared to the healthy shoulders in resting position. The difference in anterior-posterior translation during abduction was not statistically significant. Nevertheless, the authors remarked that even a 1-2 mm increase in anterior translation may be clinically significant as so-called micro-instability. Interestingly, the authors did not find any differences in anterior-posterior translation during internal and external rotation. The study moreover didn't recognize any significant differences in translation during an apprehension manoeuvre testing (Kim et al., 2017).

Peltz and colleagues investigated glenohumeral translations before and after Bankart repair during apprehension testing and found a significantly more anteriorly positioned humeral head in the instability population compared to healthy controls. Surprisingly, the overall contact path did not differ between the two groups, suggesting that the position of the humeral head, more than the translational motion, creates the sensation of apprehension. Bankart repair did result in a posterior displacement of the mean contact location, but the accompanying loss of external rotation may have been a confounding factor (Peltz et al., 2015). Di Giacomo examined the conjoint sling effect in live patients using an open MRI system by quantifying humeral head translation in a "resting" and "active" apprehension position. The authors reported a significant posterior translation of the humeral head during active isometric tensioning of the conjoint tendon, which was not present in the resting position or in healthy controls. The study demonstrated an in-vivo stabilizing effect of the conjoint muscle after Latarjet procedure (Di Giacomo et al., 2015).

In conclusion, refined *in-vivo* techniques allow for greater understanding of shoulder biomechanics and pathomechanics. The findings of *in-vivo* studies are also of value in regards to implementation of parameters in cadaveric or computational models. In the future, expansion of the field of *in-vivo* shoulder studies will hopefully continue to improve our understanding of the biomechanical principles governing the glenohumeral joint.

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Chapter 4: Morphology of Anterior Glenoid Bone Grafts

"Confidence is what you have before you understand the problem."

Woody Allen

Overview

This chapter focuses on the role of graft choice in the accurate restoration of glenoid articular surface. Biomechanical and clinical evidence regarding the role of accurate reconstruction of joint congruity and constraint is discussed. Data from the literature is reviewed, as well as the results of our own cadaveric morphological study.

4.1 Graft options

4.1.1 Introduction

The results of the biomechanical studies described in the previous chapter led to a deeper appreciation of the role played by the articular surface of grafts used in the restoration of shoulder instability. The biomechanical evidence supports the application of bone grafts as restorative or augmentative measures for anterior glenoid bone loss, and not as physical barriers to humeral head translation (Montgomery et al., 2005)(Ghodadra et al., 2010). As such, researchers started paying greater attention to the morphological specifications of bony grafts. In the next section, we will offer a brief overview of the most relevant graft options in contemporary glenoid reconstructive surgery for recurrent instability.

The section rendered below is adapted from *Willemot, L. B., Elhassan, B. T., & Verborgt, O. (2018). Bony Reconstruction of the Anterior Glenoid Rim. The Journal of the American Academy of Orthopaedic Surgeons, 26(10), e207–e218.*

4.1.2 Coracoid Process Transfers

Coracoid process transfer procedures have the longest and most successful track record of any glenoid rim reconstruction technique. The original technique, published by Latarjet in 1954, described an osteotomy of the coracoid process between the coracobrachial and pectoralis minor muscle origin. The coracoid process was transferred to the anterior glenoid neck and fixed with a screw through a longitudinal subscapularis split. Although not completely understood, the stability was believed to stem from the augmented antero-posterior glenoid diameter, the dynamic sling effect of the transplanted conjoint tendon intersecting with the subscapularis tendon, and the capsular reinforcement with coraco-acromial ligament remnant. In a technique taught by Bristow, published in 1958, a similar osteotomy was described, but the graft was transferred to the glenoid neck through a vertical slit in the subscapularis musculotendinous junction and sutured in place. Both techniques proved successful and were modified by later authors, blurring the distinction between both eponymous techniques. Coracoid transfer procedures for the treatment of anterior shoulder instability therefore gained widespread popularity as “Bristow-Latarjet procedures”, leading to some confusion in the literature. Certain authors designate techniques that require only the coracoid tip as “Bristow-procedures” and techniques using the entire coracoid process as “Latarjet-procedures”. The distinction may be subtle, but the techniques are believed to differ biomechanically in their respective stabilizing mechanism (Giles et al., 2014). For a time it was speculated that coracoid transfer procedures stabilized the humeral head by physically “blocking” anterior dislocation. However, recent biomechanical research has since acknowledged the importance of the conjoint sling as the primary stabilizer of the procedure (Wellmann et al., 2012)(Yamamoto et al., 2013). Nevertheless, some studies have emphasized the need for bony reconstruction in the presence of significant glenoid deficiency (Barrett-Payne et al., 2016).

In the classic Latarjet technique popularized by Walch, the coracoid is osteotomized at the ‘knee’ between the horizontal and vertical part of the process after release of the pectoralis minor by electrocautery. The osteotomy is performed with a 90 degree angled oscillating saw and results in a 2.5 -3 cm long graft. After decortication of the graft’s undersurface, the graft is predrilled and positioned on the glenoid neck between the 4 and 5 o’clock position (Fig. 4.1.). The graft is passed through a subscapularis split at the superior 2/3 and inferior 1/3 of the muscle. A hole is drilled 7 mm medial to the articular surface, depending on graft width, allowing flush or slightly medial graft placement. Fixation is achieved by malleolar screws. The authors recommend reinforcing the capsular repair by incorporating the coraco-acromial ligament remnant (Young et al., 2011). Long-term follow-up studies have shown an important reduction in recurrence rates (5.9%) after classic Latarjet procedure (Allain et al., 2011). However, up to 20% of patients without preoperative signs of arthritis go on to develop progressive osteo-arthritis postoperatively. An association with lateral graft overhang has been reported (Hovelius et al., 2012)(Lädermann et al., 2013). Proud or prominent graft position is believed to play a role in excessive pressures and abnormal joint mechanics resulting in early osteo-arthritis, while recessed or medialized grafts are associated with a higher risk of recurrence (Hovelius et al., 2012). However, prior number of dislocations, cartilaginous trauma and late stabilization may predispose patients to early arthropathy independent of graft position (Gordins et al., 2015).

In an effort to minimize incongruous articular surface reconstruction, Debeer et al. developed a modified procedure called the “congruent-arc Latarjet” (Fig. 4.1.)(Burkhart and de Beer, 2000). In this technique, the pectoralis minor origin is removed by oscillating saw to create a bleeding cancellous surface on the medial coracoid face. The process is then harvested immediately distal to the coraco-clavicular ligaments and rotated 90 degrees so that the curved coracoid undersurface is aligned with the articular surface, and the medial raw surface abuts the anterior glenoid neck. The authors recommend placement of the graft through a partial subscapularis takedown (50%) and fixation of the graft with two 4.0 or 4.5 mm cannulated screws. The rotated graft allows for greater graft surface area utilization, but creates a significant lever arm which results in a biomechanically weaker construct. The implications are contested due to lack of clinical data to support the claim. The modification does provide a better match between graft and glenoid curvature which reduces abnormal pressure distributions (Ghodadra et al., 2010). The authors report satisfactory clinical outcomes with low recurrence and complication rates, in line with the results of the classic Latarjet (Burkhart et al., 2007). There are currently no randomized clinical trials comparing classic and congruent arc Latarjet procedures in the available literature. Biomechanical experiments have not been able to demonstrate a significant difference between classic and congruent-arc Latarjet regarding joint stability or range of motion (Boons et al., 2013) Despite concerns about graft size, biomechanical and clinical studies have shown adequate surface area reconstruction using the classic Latarjet orientation. Larger glenoid defects are theoretically more accurately restored using the congruent-arc Latarjet.

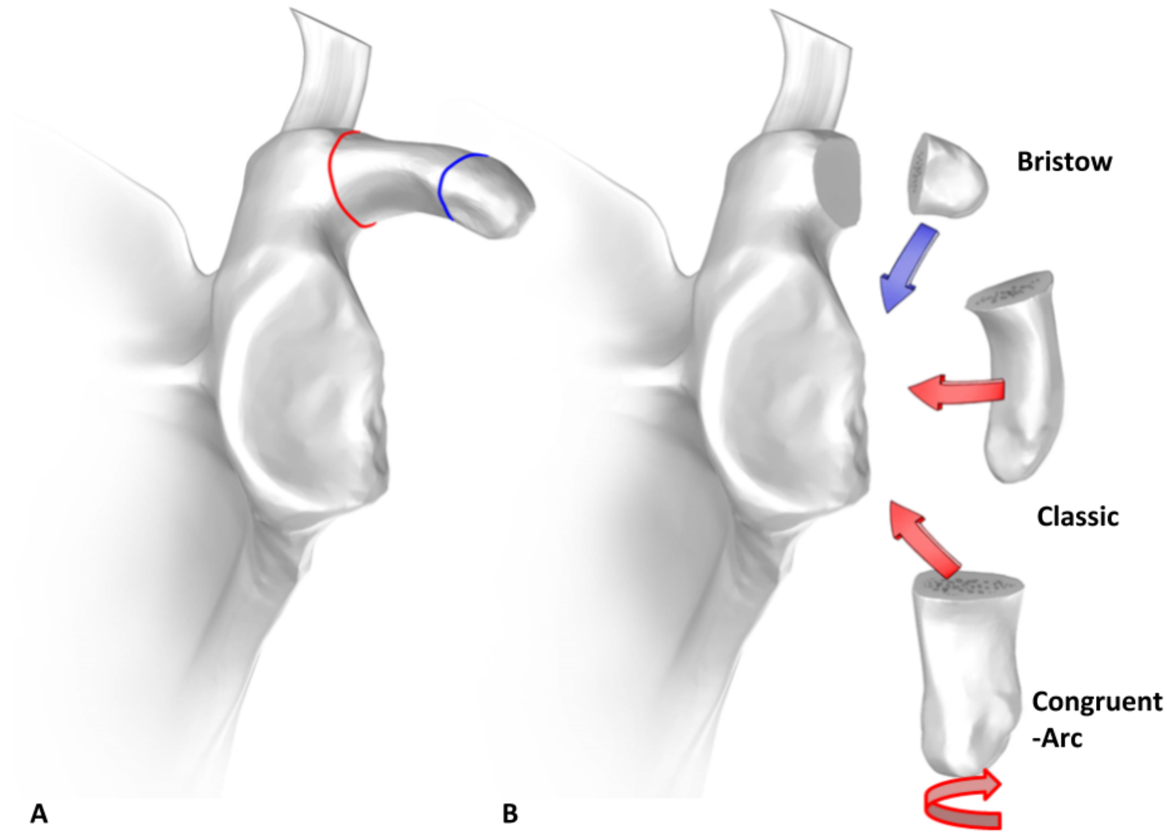

Figure 4.1

Panel A. depicting the osteotomy sites for Latarjet (red) and Bristow (B) procedures. Panel B. illustrating the Bristow, Classic and Congruent-Arc coracoid positions.

Lafosse et al. were the first to describe an all-arthroscopic Latarjet procedure. The authors argued that an arthroscopic approach would increase precision in graft placement, allow detection and treatment of concomitant pathology, minimize postoperative stiffness, facilitate rehabilitation and improve cosmetic results. The original technique involved debridement of the anterior glenoid rim, release of the soft-tissues around the coracoid process and splitting of the subscapularis muscle. The coracoid drill holes were then prepared using specialized instruments, followed by coracoid harvesting, transfer and fixation with screws through a double-barreled cannula (Lafosse et al., 2007). The authors reported good clinical outcome scores and a low recurrence rate (1 subluxation in 62 patients) after 5 year. Others have reported accurate graft positioning (94%) and high healing rates (78%) after 3 months using the same technique (Dumont et al., 2015)(Casabianca et al., 2016). The arthroscopic technique does not include a capsular or coraco-acromial ligament repair, calling into question the necessity of the repair in open procedures. The biomechanical evidence regarding the need for capsular repair is also conflicting. Boileau et al. described an alternative arthroscopic technique in which the graft was placed in a “standing” Bristow-like position and an anchored repair of the capsulo-labral complex was added. The reported clinical outcomes were similar to the open Bristow technique results. Graft non-union rate was significantly higher (20%) than after open or arthroscopic Latarjet procedures and associated with persistent apprehension. The technique was modified to a screw-free cortical button system in a Latarjet-type “lying down” position to address these issues (Boileau et al., 2016). The authors reported good clinical results without any hardware or neurologic complications. Proponents of the arthroscopic coracoid transfers claim that the procedure is not more demanding than the open version, but many remain skeptical about the learning curve, risk of complications, procedural duration and cost-effectiveness. It is generally accepted that only experienced shoulder surgeons with advanced arthroscopic skills should attempt coracoid process transfers.

With some notable exceptions, the modified Bristow on-end “standing” coracoid bone grafts, have mostly been replaced by “lying down” Latarjet-type transfers (Fig. 4.1.). Furthermore, some authors have argued in favor of transferring the conjoint tendon without bone graft for patients with minimal or no bone loss, relying solely on the conjoint sling effect for stability, as discussed in Chapter 3.

4.1.3 Free Bone Grafts

Eden and Hybbinette are credited for the first description of free autologous bone grafts in anterior glenoid rim reconstruction. The original techniques inserted tibial or iliac crest grafts under the anterior glenoid periosteum without further fixation. Later modifications included preferential use of the iliac crest in a tricortical or bicortical manner and rigid screw fixation. Unlike some bone grafting techniques aimed at blocking anterior humeral translation, these procedures were developed to prevent Hill-Sachs engagement and to restore the glenoid vault. Glenoid reconstruction by iliac crest graft has historically been associated with early post-operative degenerative changes. However, the multitude of reconstructive techniques with varying degrees of lateral overhang, and variability in osteoarthritis classifications precludes accurate estimation of post-stabilization arthritic rates. Some authors have suggested interposing the capsule between glenoid and graft in the hope of minimizing micro-instability and avoiding direct abrasion of the humeral head by the iliac crest graft. Others have argued that capsular reattachment may limit range of motion in glenoids with significant bone loss and cause arthropathy due to the increased intra-articular pressure (Itoigawa et al., 2016). Iliac crest graft reconstruction is at a biomechanical disadvantage compared to coracoid transfer procedures considering the absence of a sling effect (Wellmann et al., 2009). However, iliac crest grafts have been shown to successfully restore stability in failed Bristow-Latarjet procedures, calling into question whether conjoint tendon transfer is always required. The iliac crest is a convenient source of customizable autologous bone grafts, but is associated with significant immediate and sometimes persistent pain at the donor site (Almaiman et al., 2013).

4.1.3.1 Iliac Crest Bone Grafts

Hutchinson et al. described augmenting the anterior glenoid with a tricortical iliac crest graft (4 cm wide and 3 cm high) in epileptic patients. In this technique, the graft is positioned with the crest side facing laterally. The cortex is burred away until the graft is flush and congruous with the native glenoid. Afterwards, the capsule is reattached to the screw heads, rendering the construct intra-articular. The authors reported no further dislocation but some restriction in range of motion in their study population (Hutchinson et al., 1995). Similar techniques have placed the tricortical graft with the distal cancellous graft side abutting the glenoid neck and the crest facing anteriorly. Warner et al. reported placing a (3 cm wide and 2 cm high) tricortical graft with the inner table facing laterally and the crest side superiorly in an intra-articular configuration. The authors report no further instability and limited loss of motion with return of all patients to pre-injury levels of sport participation in their cohort (Warner et al., 2006)(Fig. 4.2. and 4.3).

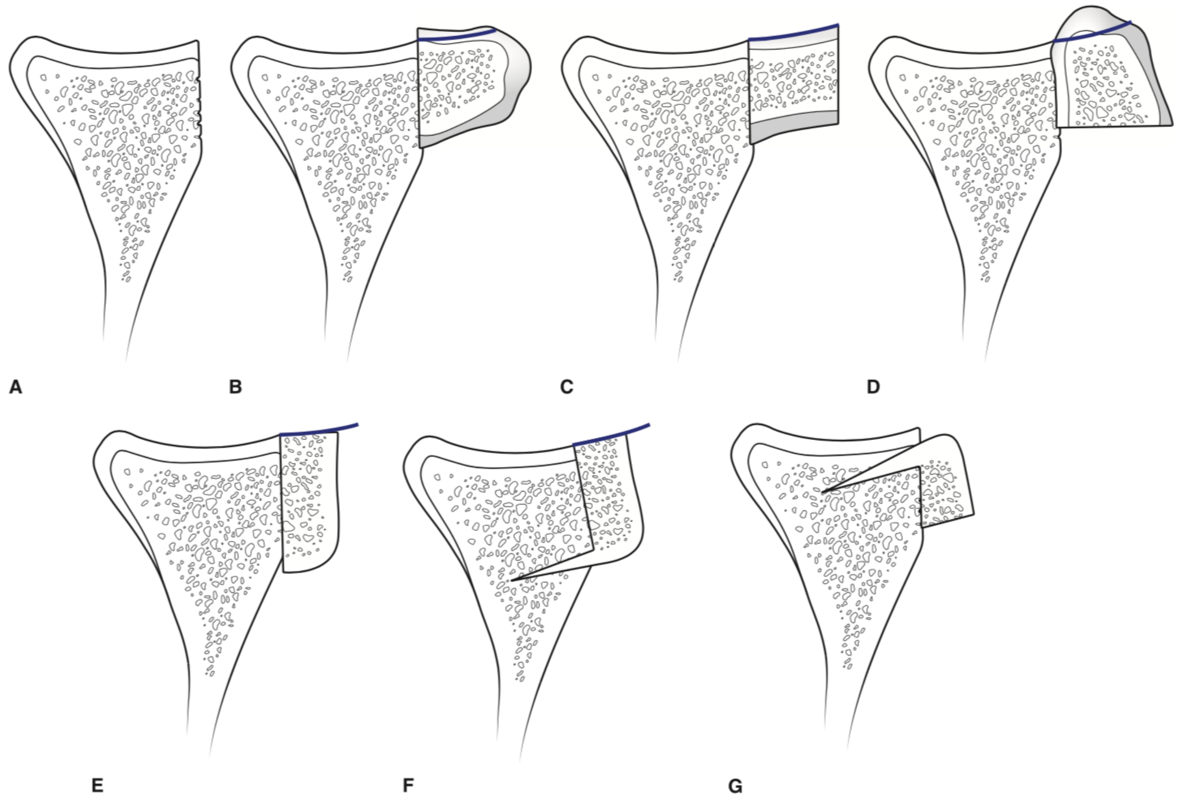

Figure 4.2
Diagrams depicting iliac crest graft orientation.The blue lines indicate final graft articular surface after positioning and reshaping when applicable. A, Glenoid with substantial anterior bone loss. B, Tricortical iliac crest graft described by Taverna et al. C, Tricortical iliac crest graft described by Warner et al. D, Tricortical iliac crest graft described by Hutchinson et al. E, Bicortical iliac crest graft described by Churchill et al. F, Bicortical iliac crest graft used in the J-bone technique. G, Bicortical iliac crest graft used in the Alvik technique.

Matsen and Lippitt published a bicortical iliac crest graft technique. A (2.5 cm x 2.5 cm x 1 cm) graft is harvested from the outer cortex of the superolateral iliac crest. The graft is positioned such that the large cancellous surface lies against the glenoid neck and the narrow cancellous surface faces laterally (Churchill et al., 2001). The articular side of the graft is burred down to the level of the glenoid surface and the capsule is reattached at the interface between graft and glenoid. The authors reported good clinical outcomes in all but one of the 20 patient cohort. Steffen and Hertel reported on a similar technique using a bicortical crest graft. The authors emphasized accurate contouring of the cancellous surface before covering it with capsulo-labral tissue. A distinction is made between restoration of the normal limited gliding of the humeral head over the glenoid surface (micro-instability) and the prevention of dislocation (macro-instability). According to the authors, the low incidence of postoperative osteo-arthritis in their population was a direct result of the fibrocartilaginous tissue interposition between the bone graft and the humeral head, and the restoration of micro-stability (Steffen and Hertel, 2013) (Fig. 4.2. and 4.3)

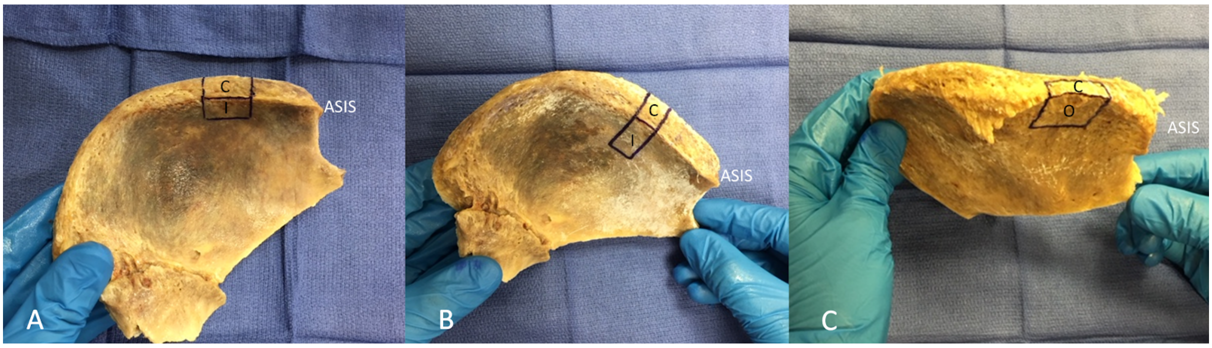

Figure 4.3
Different techniques for the harvesting of structural iliac crest grafts. (A) Tricortical iliac crest graft. (B) Alternate tricortical iliac crest graft. (C) Bicortical iliac crest graft. I=inner table, O=outer table, C=crest.

Similarly to the arthroscopic Bristow-Latarjet procedure, an arthroscopic Eden-Hybbinette procedure was developed to improve diagnostic and therapeutic accuracy, and minimize soft-tissue dissection and scar formation (Fig. 4.4). Additionally, and in contrast with arthroscopic coracoid transfers, free bone grafts can be introduced through the rotator interval without disturbing the subscapularis muscle (Verborgt et al., 2013). Subscapularis injury, a known complication of anterior glenoid bone grafting, can lead to postoperative loss of motion and weakness. An all-arthroscopic tricortical intra-articular technique in lateral decubitus was published by Scheibel and colleagues (Kraus et al., 2014). The authors reported significant improvement in clinical scores, no recurrences and anatomical remodeling of the graft. Taverna et al. published a similar all-arthroscopic tricortical (2 cm x 1 cm) technique in beach chair position. The procedure involved pulling the graft through the rotator interval with the help of transglenoid sutures. In a later modification of the technique, fixation was achieved with cortical suture buttons instead of screws, thus creating the first screw-free anterior bone grafting procedure for glenohumeral instability (Taverna et al., 2018). Moreover, Giannakos et al. recently published their satisfactory results with an all-arthroscopic bicortical iliac crest graft procedure using arthroscopic Latarjet instruments for the revision of failed coracoid transfers (Giannakos et al., 2017).

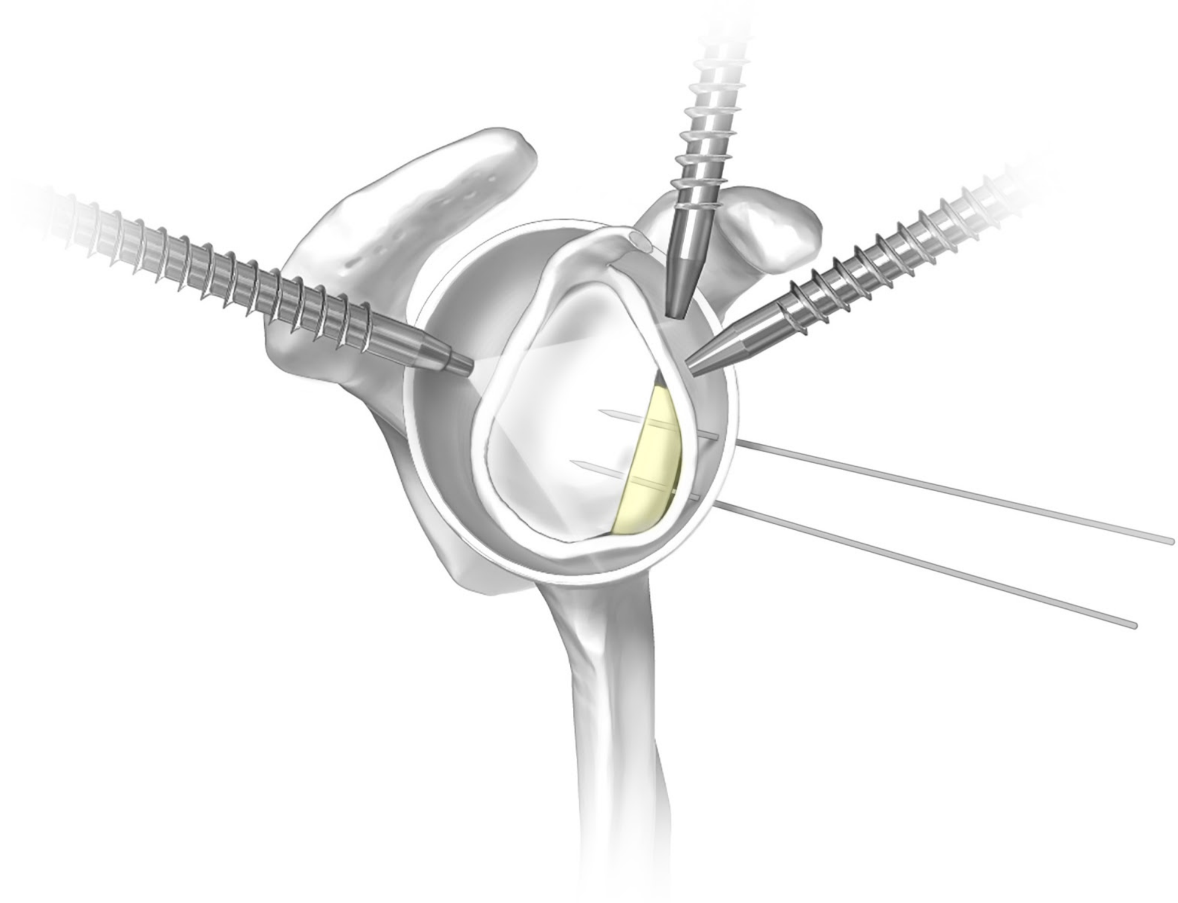

Figure 4.4
Artist rendition of an arthroscopic iliac crest grafting procedure. The graft is introduced through the rotator interval and temporarily fixed with K-wires on the anterior glenoid neck. Adapted from Taverna E, D'Ambrosi R, Perfetti C, Garavaglia G: Arthroscopic bone graft procedure for anterior inferior glenohumeral instability. *Arthroscopy techniques* 2014;3:e653-660.

The Lange modification of the Eden-Hybbinette procedure gained popularity as the “Alvik glenoplasty” in Northern Europe. The procedure involves wedging a 2 cm x 2 cm x 0.5 cm bicortical outer crest graft in a trough created on the anterior glenoid neck with the graft cortex facing laterally (Fig. 4.2). Low recurrence rates and good clinical and radiographic results have been published using the technique, despite concerns about early postoperative osteo-arthritis (Wildner et al., 1994). The technique boasts an implant-free fixation method for anterior glenoid reconstruction. This is relevant since hardware related complications, such as screw loosening, pull-out, breakage and malposition, are the most frequent cause of intra and postoperative complications in anterior glenoid reconstruction (Griesser et al., 2013). A variant of this technique dubbed the “J-bone technique”, due to the shape of the graft, similarly relies on the tapered shape of the long leg of the bicortical graft (15 cm x 15 cm x 5 mm) for fixation. A 10 mm deep glenoid osteotomy is created at a 30 degree angle, 5 mm medial to the glenoid rim. The procedure requires subscapularis tenotomy and the graft is left intra-articularly after capsule closure. Contrary to the Alvik procedure, the graft is turned so that the cancellous part of the short leg faces laterally (Fig. 4.2). Reported outcomes indicate high patient satisfaction without recurrence, loss of motion or strength and high rates of sport participation (Anderl et al., 2016). Osteolysis or graft resorption is a frequent finding after glenoid rim reconstruction which may lead to prominent hardware and recurrent instability. Bone resorption in function of the level of strain transmitted through the it is known as the "mechanostat concept" or "Wolff's law". Hardware can disturb this normal process, possibly leading to excessive resorption around the stiff metal screws. The screw-free J-bone operation has demonstrated anatomical remodeling of rectangular bone grafts to the presumed original glenoid shape within the first year. An all-arthroscopic version of the procedure was also reported (Moroder et al., 2018). The authors describe the insertion of a spiked anterior glenoid retractor through a subscapularis split to create a "waterslide" for the graft. An earlier technique used transglenoid sutures to approximate the graft, but this was modified to a specialized impactor capable of holding and safely manipulating the graft. Reported clinical and radiologic outcomes are similar to the open technique. One drawback of implant free bone grafting procedures is that longer immobilization is typically required postoperatively to allow for bony healing before active motion is allowed.

We briefly mention the use of allogeneic ICBG for the reconstruction of anterior glenoid bone loss. Mascarenhas and colleagues reported satisfactory clinical outcomes and bony healing using allogeneic ICBG in young patients with large bony defects. However, the study included only 10 patients, followed for 16 months. There are no further series of allogeneic iliac crest graft in the literature. Presumably, the cost and risks of allogeneic sourced bone outweighs the benefits and availability of autologous iliac crest grafts (Mascarenhas et al., 2014).

4.1.3.2 Osteochondral Grafts

The use of rigid bone grafts for the reconstruction of anterior glenoid rim defects may play a role in the incidence or acceleration of osteoarthritis in post-stabilization arthropathy (Hovelius et al., 2012)(Lädermann et al., 2013). Therefore, some authors have proposed transplanting grafts containing articular cartilage. These include both osteochondral autografts and allografts. The only osteochondral autograft in clinical use today is the distal clavicle autograft (Tokish et al., 2014). In regards to allografts, the distal tibia graft has shown significant promise. Conversely, despite the good outcomes which have been described using glenoid allografts, the technique has not gained widespread popularity due to graft availability issues.

The use of distal clavicle autografts was originally promoted by Tokish and colleagues as an arthroscopic solution to the glenoid bone loss problem. The technique outlined by the authors describes the harvest of 6 to 8 mm of distal clavicle, transposition of the fragment to the glenoid neck and fixation by means of bone anchors or a 3.5 mm screw (Tokish et al., 2014). Evidence from the literature on distal clavicle resection for osteolysis has shown that the procedure is well tolerated in athletes and allows an early return to sports (Charron et al., 2007). Cadaveric studies have revealed the ability of distal clavicle autografts to reconstruct defects up to 44% of glenoid width, which is significantly greater than the reconstructive capabilities associated with classic coracoid transfers (Kwapisz et al., 2018). Moreover, pressure mapping experiments have revealed lower mean pressures when compared to Congruent-Arc Latarjet and similar contact surface areas (Petersen et al., 2016). Limited clinical data is available on this promising graft type and technique.

Non-anatomic coracoid process transplantations have been associated with scapular dyskinesis (Carbone et al., 2016), increased superior humeral head translation (Degen et al., 2013), poor glenoid arc reconstruction (Ghodadra et al., 2010), absence of cartilage reconstitution, neurovascular complications (Griesser et al., 2013), and subscapularis muscle injury. Moreover, iliac crest autografts can be associated with troublesome donor site morbidity (Pollock et al., 2008). Fresh or fresh-frozen osteochondral allografts have therefore attracted attention as an alternative for coracoid or iliac crest grafts. Skeptics of allograft usage have questioned the rationale by pointing to the risk of disease transmission, prohibitive cost, low viability of chondrocytes and the spontaneous appearance of a fibrocartilaginous layer on the surface of bone grafts in traditional grafting procedures (Auffarth et al., 2008)(Auffarth et al., 2018). Techniques using allogeneic grafts in glenoid reconstruction do not seem to be associated with higher rates of graft resorption or non-union than autologous techniques (Sayegh et al., 2014). Glenoid allografts and distal tibia allografts are discussed below. A description of the more seldomly used femoral head allograft is not included due to scarce literature (Weng et al., 2009).

Tjoumakaris et al. reported good short term outcomes using a fresh-frozen glenoid allograft for the treatment of a significant bipolar lesion (Tjoumakaris et al., 2008). Skendzel and Sekiya later introduced an arthroscopic version of the technique, avoiding the need for subscapularis takedown and allowing for more aggressive rehabilitation. Very limited clinical and radiographic follow-up is available for these cases. However, the authors stressed the theoretical benefits of their technique which is unique in achieving restoration of both cartilaginous surface and labrum (Fig. 9.) (Skendzel and Sekiya, 2011).

Provencher et al. pioneered the use of fresh tibial plafond allografts for the restoration of anterior glenoid defects. The graft is transported in a sterile medium from the donor to the operating room without freezing. The matching radius of curvature, cartilaginous surface, dense subchondral bone stock and lower risk of contamination during harvest make the lateral tibial plafond an appealing choice. The grafts are also more readily available from tissue banks than glenoid allografts (Provencher et al., 2009). The authors emphasized the comparable radii of curvature of the lateral tibial plafond and glenoid articular surfaces (Fig. 10.). This was confirmed by contact measurements and CT surface analysis (Bhatia et al., 2013)(Noonan et al., 2014). The authors reported successful incorporation of the graft, yet only limited clinical and radiographic results are available for this technique.

An overview of the enumerated graft options is given below (Fig. 4.5).

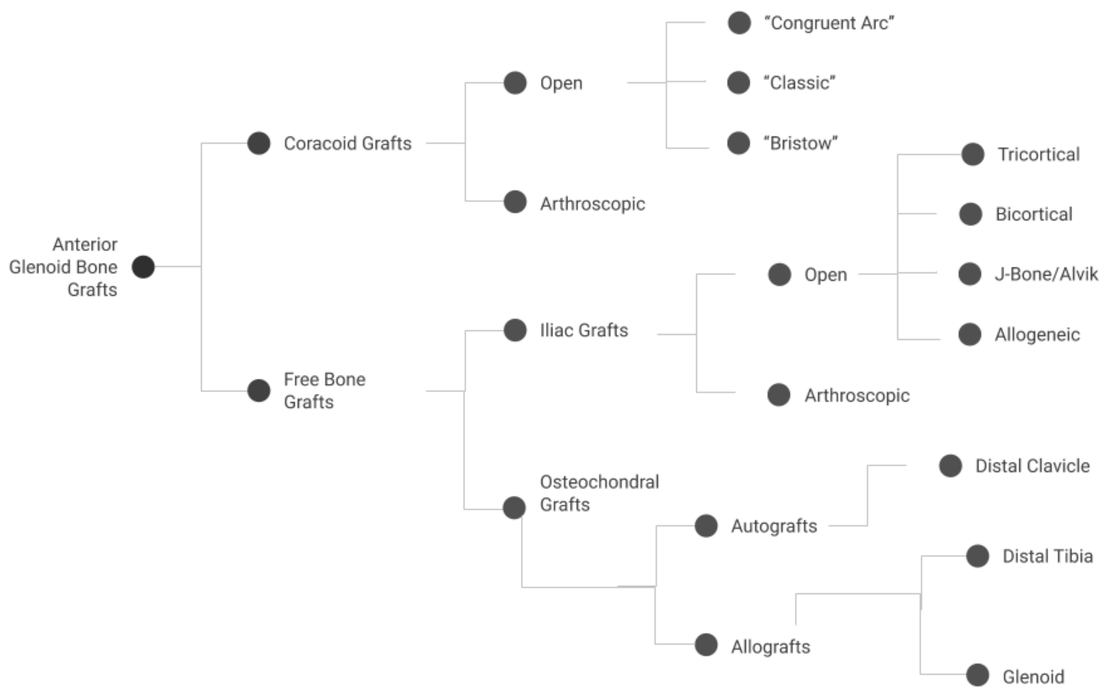

Figure 4.5
An overview of relevant graft options is given in the choice tree.

4.2 Graft Surface Morphology Analysis

4.2.1 Introduction

Burkhart and colleagues were amongst the first the introduce a modification to the Latarjet procedure specifically aimed at increasing bony congruence. The authors suggested rotating the coracoid bone graft 90° so as to position the graft with the "underside" facing the humeral head, instead of it facing the glenoid neck as in the classic Latarjet (Fig. 4.1). Early work by Ghodadra and colleagues had already indirectly demonstrated the superiority of ICBG and congruent-arc Latarjet over classic Latarjet in regards to shape, indicating significantly reduced peak contact stresses and more adequately restored contact areas (Ghodadra et al., 2010). The coracoid process, moreover, exhibits a greater width than thickness, which theoretically increases the surface area available for reconstruction. Several studies, including ours, confirmed this speculation by direct analysis of graft surface characteristics (Willemot et al., 2017)(Noonan et al., 2014)(Hantes et al., 2010). Whether or not the coracoid surface is sufficient for the restoration of glenoid bone loss, depends on the size of the lesion. Paladini and colleagues investigated the restorative capabilities in patients with at least 20% bone loss and concluded that the graft satisfactorily reconstructed the glenoid surface (Paladini et al., 2016). However, this study analyzed 2D axial CT images as opposed to 3D articular renderings. Moon et al., similarly analyzed patients with a mean of 25% glenoid bone deficit and reported restoration to within 1%-2% of the speculated intact condition using a Classic Latarjet technique (Moon et al., 2015). Burkhart and de Beer had suggested that the coracoid undersurface would better replicate the glenoid articular surface, due to its innate curved undersurface (Burkhart and Debeer, 2000). The first CT-based analysis of surface characteristics of the coracoid process by Armitage and colleagues indicated that the curvature did match the intact glenoid longitudinal radius of curvature (ROC), yet the study was limited to the measurement of longitudinal ROC on intact scapulae with the coracoid process in situ (Armitage et al., 2011). Later, more comprehensive, studies performed by Dehaan et al., Noonan et al., and ourselves, investigated morphological characteristics of anterior glenoid bone grafts in detail and are discussed in the next subheading (Dehaan et al., 2013)(Noonan et al., 2014)(Willemot et al., 2017). Significant concerns exist regarding the biomechanical fixation strength of the Congruent-Arc Latarjet coracoid position. Some authors have argued that the greater leverage force placed on the screws as a result of the graft width, may lead to premature construct failure. Biomechanical experiments have supported these claims, yet extrapolation of the required construct stability to live patients has proven difficult. Nevertheless, the same study indicated that the Congruent-Arc procedure trended to more closely recreate intact contact patterns compared to the Classic Latarjet (Giles, 2012).

Increased awareness of graft resorption after coracoid transfer, leading to recurrence, pain and hardware problems, has had a significant impact on the more traditional “bigger is better” approach in anterior glenoid bone grafting (Di Giacomo et al., 2013)(Zhu et al., 2015). The risks of construct failure and other graft related complications such as resorption, fracture and non-union are discussed in further detail in Chapter 5. Contoured and native bone grafts such as the ICBG in tricortical, bicortical or J-bone configuration, as well as distal clavicle autografts, distal tibia allografts and glenoid allografts were put forward as alternatives to the coracoid process in the hope of decreasing the risk of postoperative joint incongruency. Pressure mapping experiments have revealed significantly lower peak forces and greater contact area using distal tibia grafts compared to the Latarjet procedure (Bhatia et al., 2013). Such findings helped to propel research into the surface morphology of various graft options in anterior glenoid bone grafting. In the next subheadings we present our findings of surface characteristic analyses using various anterior glenoid bone grafts. This work was originally published as “*Restoration of Articular Geometry Using Current Graft Options for Large Glenoid Bone Defects in Anterior Shoulder Instability.” by* Willemot, L. B., Akbari-Shandiz, M., Sanchez-Sotelo, J., Zhao, K., & Verborgt, O. in the *The Journal of Arthroscopic & Related Surgery in 2017.*

4.2.2 Methods

4.2.2.1 Anatomic Specimens

Eight unpaired fresh frozen male human cadaver shoulders (4 right and 4 left shoulders) were obtained from our institution’s anatomical bequest program after Institutional Review Board approval for this study. A total of 16 specimens were originally screened by clinical inspection, review of medical charts, and fluoroscopic evaluation. Inclusion criteria were male specimens with a maximum age of 75 years. Exclusion criteria were the presence of degeneration, trauma, dysplasia, previous instability, or surgery. Eight specimens exhibiting such signs were excluded from the study. The mean age of the selected 8 donors was 67.9 years (range, 53 to 75 years), mean height was 174.4 cm (range, 165 to 185 cm), and mean weight was 85.5 kg (range, 54 to 113 kg). All soft tissues were removed from the cadaveric specimen, except for the glenoid cartilage and labrum. The scapulae were potted in resin and positioned on a custom tray for manipulation and imaging. Eight ipsilateral iliac crests and distal tibias were harvested from 8 unrelated male donor specimens for reconstructive graft procurement as described below (the mean age of these donors was 70.6 years, with a mean height of 177.5 cm and a mean weight of 89.7 kg).

4.2.2.2 Experimental Conditions

After scanning each intact scapular specimen as detailed below, an anterior glenoid defect was created. A line was drawn from the supraglenoid to the infraglenoid tubercle. Perpendicular to this axis, the maximal anteroposterior (AP) diameter was measured with digital calipers. A second parallel superoinferior (SI) line was drawn at the anterior 25% of the AP width. A 25% anterior glenoid bone defect was then created with an oscillating sagittal saw along this line (Fig 4.2)(Saito et al., 2005)(Yamamoto et al., 2010).

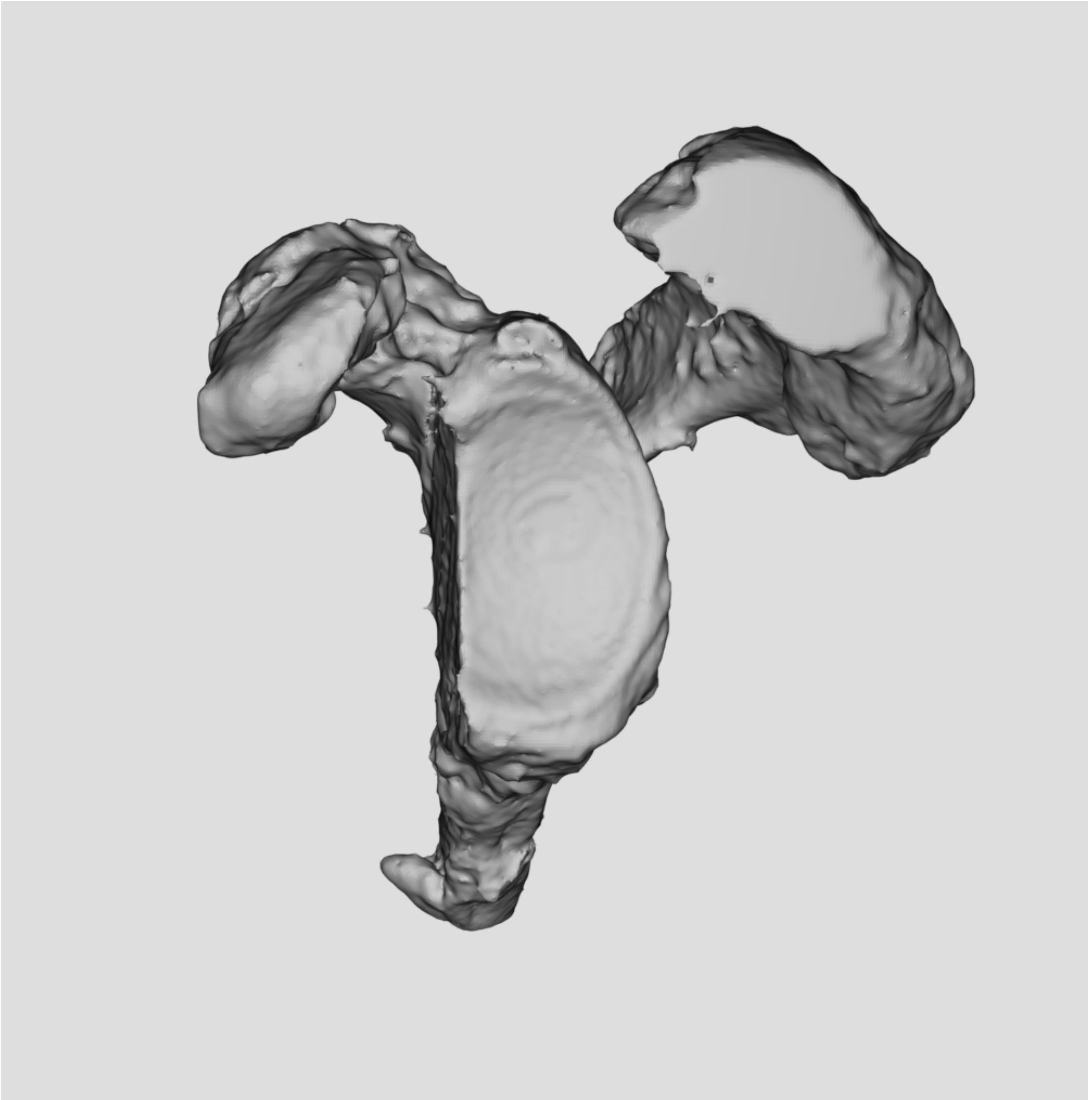

Figure 4.6
Example of a 3D “cartilaginous” CT reconstruction of a left glenoid after creation of an anterior 25% glenoid defect parallel to the superior-inferior axis.

Afterwards, the articular surface was reconstructed in 7 sequential conditions: (1) classic Latarjet, (2) modified congruent-arc Latarjet (CA Latarjet), (3) tricortical iliac crest inner table and (4) outer table, (5) bicortical iliac crest, (6) distal tibia, and (7) glenoid osteochondral graft. The CA Latarjet modification, as described by Burkhart et al., was performed first, making the curved inferior coracoid side the new articular surface (Burkhart and de Beer, 2000). The classic Latarjet required decortication of the inferior coracoid side and was thus performed afterwards. The graft was positioned so that the lateral cortex aligned with the glenoid face as described by Mizuno et al. and Young et al. For the iliac crest conditions, a 2 cm long, 1 cm high tricortical iliac crest graft was positioned such that the inner table cortex became an extension of the glenoid surface (Mizuno et al. 2008)(Young et al., 2008)(Kraus et al.2014). The graft was then repositioned to align the outer table cortex with the joint surface for the outer crest condition. The tricortical graft was subsequently split along the crest, and the outer table was used for the bicortical condition as described by Rockwood and Matsen, using the distal cancellous surface to reconstruct the articular face (Rockwood and Matsen, 2007). The distal tibia osteochondral graft was harvested from the ipsilateral tibial plafond of an extraneous donor. A graft was taken from the lateral third of the articular surface as described by Frank and colleagues (Frank et al., 2017). For the final condition, the previously osteotomized anterior glenoid fragment of one of the other scapulae was affixed to the specimen's glenoid neck. The source specimen for the glenoid graft was randomly selected. This simulated the procurement of a glenoid osteochondral allograft as reported by Skendzel and Sekiya (Skendzel and Sekiya, 2011). The reconstructive procedures were performed serially on all glenoid specimens. In each condition the graft was fixed to the glenoid neck with two 1.2 mm Kirschner wires. The grafts were placed flush with the glenoid cartilaginous articular surface and centered on the defect, allowing for maximal reconstruction of the inferior glenoid circle (Huysmans et al., 2006).

4.2.2.3 Imaging

All specimens were scanned with a dedicated research (CT) scanner (Definition FLASH dual source scanner, Siemens, Munich, Germany) using an ultra-high resolution mode protocol, before and after the creation of the glenoid defect and after each iterative repair.

4.2.2.4 Three-Dimensional (3D) Model Creation and Measurements

The raw digital imaging and communications in medicine data were loaded in the segmentation software package Mimics 13.0 (Materialise, Ann Arbor, MI) for the creation of 3D models. Segmentation was performed at 2 threshold levels. The first included all available tissues in the region of interest such as labrum, cartilage, cortical, and cancellous bone for the creation of a "cartilaginous" articular surface 3D model (Fig. 4.6). The second segmentation retained only bony tissue for analysis of the underlying "subchondral bone" articular surface. The models were then loaded in the open-source triangulated 3D mesh processing software Meshlab (Meshlab v1.3.3, 3D-CoForm project) for further processing (Cignoni et al., 2008). Analogous to the methods of Noonan et al., an axial planar section was taken at the level of the widest AP diameter of the intact glenoid, parallel to the AP axis. Subsequently, a coronal section, parallel to SI axis, was created 1 mm anterior to the defect edge after superimposing the defect glenoid model onto the intact glenoid. This was done to avoid artifacts related to the creation of the osteotomy (Fig. 4.7). The CloudCompare program (OpenSource Project, www. cloudcompare.net) was used to process the planar sections created as described above. The articular surfaces were segmented out manually by selecting only the region between the most lateral points of the glenoid vault. The deformable labrum was not included in the segmentation. Curvature was computed by calculating the radius of curvature (ROC) of the best-fitting circle to the section via a custom Matlab program. Concave curves were given positive values, and convex curves negative values. ROC findings were then converted to curvature (k) to allow continuous statistical comparison of negatively and positively inflected curves (1/k=ROC). Additionally, the program calculated the length of each section and maximal depth of each section. The subchondral articular step-off at the graft-glenoid interface was evaluated by measuring the distance between the graft surface and the original surface at the graft-glenoid interface (Fig 4.4).

4.2.2.5 Statistical Analysis

Due to a lack of available clinically relevant data on glenoid surface geometry, accurate power calculation was not possible. The traditionally accepted number of specimens for cadaveric interventional studies at our institution was deemed sufficient (Yamamoto et al., 2009)(Halder et al., 2001). Only descriptive statistics were reported in this paper due to the likelihood of an underpowered experiment. All results are presented as mean (standard deviation [SD]) and percentage of the intact condition.

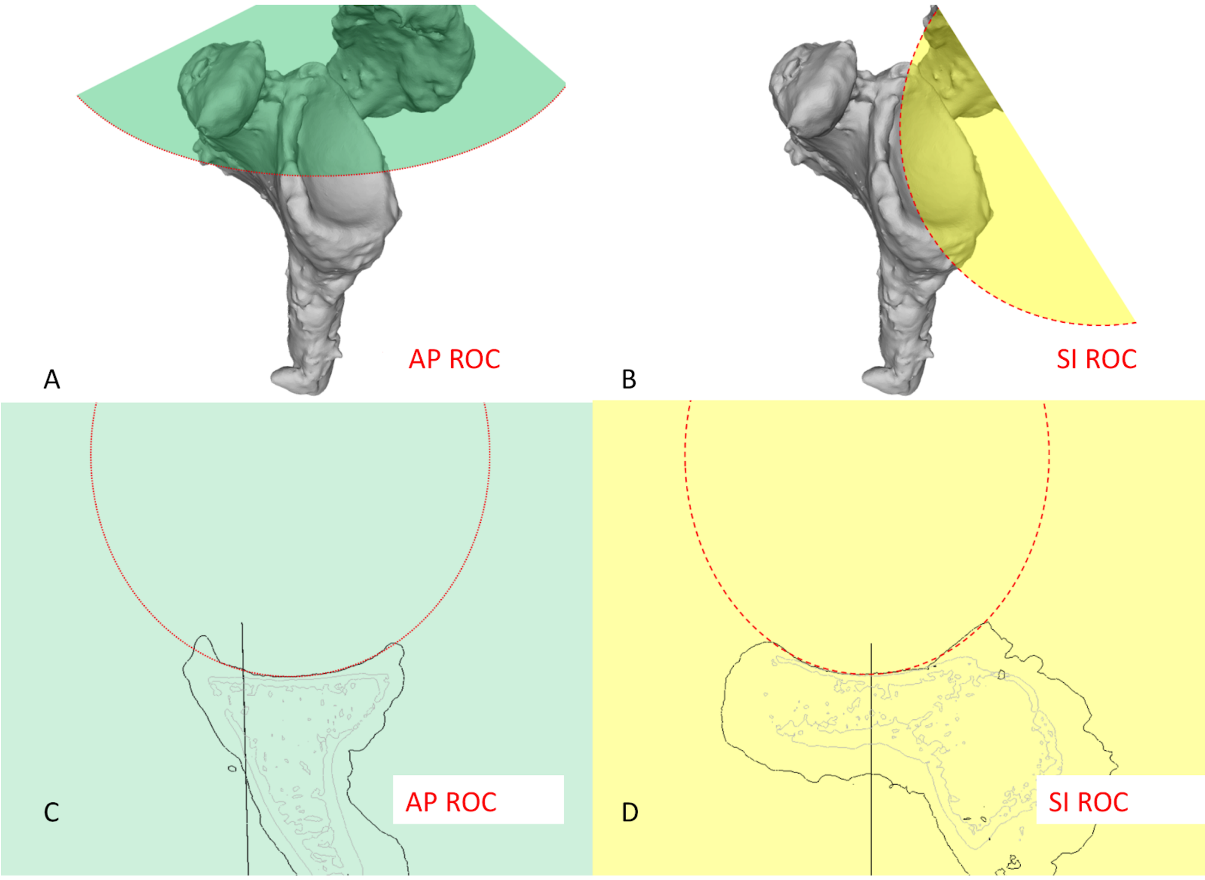

Figure 4.7
Illustration of radius of curvature measurements. (A) “Cartilaginous” three-dimensional (3D) model reconstruction of a left glenoid in the intact condition. The red dotted curve indicates the site of measurement for the anteroposterior (AP) or axial radius of curvature (ROC). Green area indicates the axial planar section. (B) The 3D reconstruction of the same glenoid with red dashed curve indicating the superoinferior (SI) or coronal ROC. The yellow area indicates the coronal planar section. (C) The two-dimensional (2D) representation of the AP or axial planar sections. The red dotted curve demonstrates best-fitting circle. (D) The 2D

representation of the SI or coronal planar sections. The red dashed curve demonstrates best-fitting circle.

4.2.3 Results

4.2.3.1 Glenoid Width and Surface Area

Maximal bony glenoid width was reduced from 28.3 mm (0.8) in the intact condition to 20.0 mm (1.6) after creation of the defect, or a relative loss of 29.2%. Bony surface area was diminished from 964.0 mm2 (58.8) in the intact, to 772.5 mm2 (45.4) in the defect condition, corresponding to a relative loss of 19.9%. Reconstruction of width and surface of the bony glenoid was optimal with the glenoid allograft, achieving reconstruction of 97.4% and 99.4% of the intact state. Bicortical iliac crest and classic Latarjet produced the second (92.4%) and third (89.3%) best matches for width, whereas classic Latarjet and bicortical iliac crest (93.2% and 97.4%) produced the second and third most accurate surface reconstruction (Table 4.1).

4.2.3.2 Glenoid Depth

Maximal cartilaginous glenoid fossa depth decreased 35.9% from 3.1 mm (0.7) to 2.0 mm (0.5) after creation of the defect. Most accurate restoration of glenoid depth was seen using the CA Latarjet, attaining 101.0% of original depth. Tibial allograft and glenoid allograft reconstruction produced the second and third closest matching results with 98.9% and 95.3%, respectively (Table 4.1).

4.2.3.3 Glenoid Curvature

Axial (AP) curvature of the glenoid measured 0.039 mm^{-1} (0.003) for the native glenoid. Ideal reconstruction of curvature was achieved by the glenoid allograft, with an accuracy of 97.5%. Classic latarjet and iliac crest bicortical graft were the next closest matches with 108.7% and 91.2% of the intact curvature (Fig. 4.9). SI or coronal curvature measured 0.040 mm^{-1} (0.004) at the site of the osteotomy. Closest reconstitution of the intact condition was achieved by the glenoid allograft with 102.6% of the original curvature. Tibial allograft and classic Latarjet produced the second and third most similar curves with 115.0% and 55.9% (Fig 4.9; Table 4.1).

4.2.3.4 Articular Step-Off

Analysis of the subchondral bone showed the smallest articular step-off for the glenoid allograft (0.06 mm). The largest step-off was seen in the bone models of the iliac crest outer table (2.5 mm), bicortical (2.3 mm), inner table (1.9 mm), and classic Latarjet (1.9 mm) grafted conditions. The CA Latarjet and tibial allograft exhibited an articular step-off of 1.4 mm and 0.4 mm, respectively (Table 4.1).

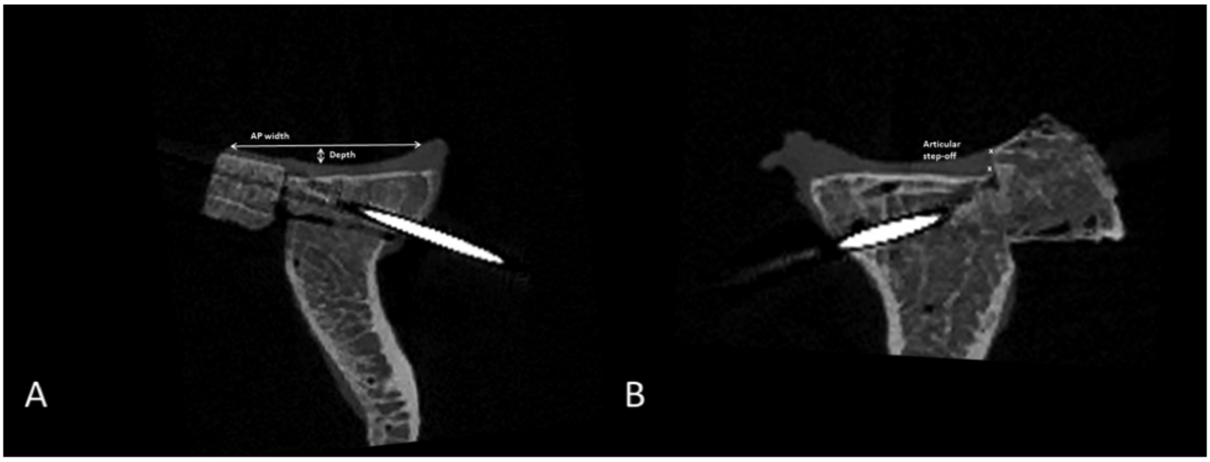

Figure 4.8
Examples of two-dimensional computed tomography axial slice width and depth measurement. (A) Horizontal double arrow indicates anteroposterior width, and vertical double arrow indicates depth of cartilaginous surface after tibial allograft on a left glenoid. (B) Asterisks indicate articular step-off measurements in the bony surface after iliac crest inner table grafting on a right glenoid.

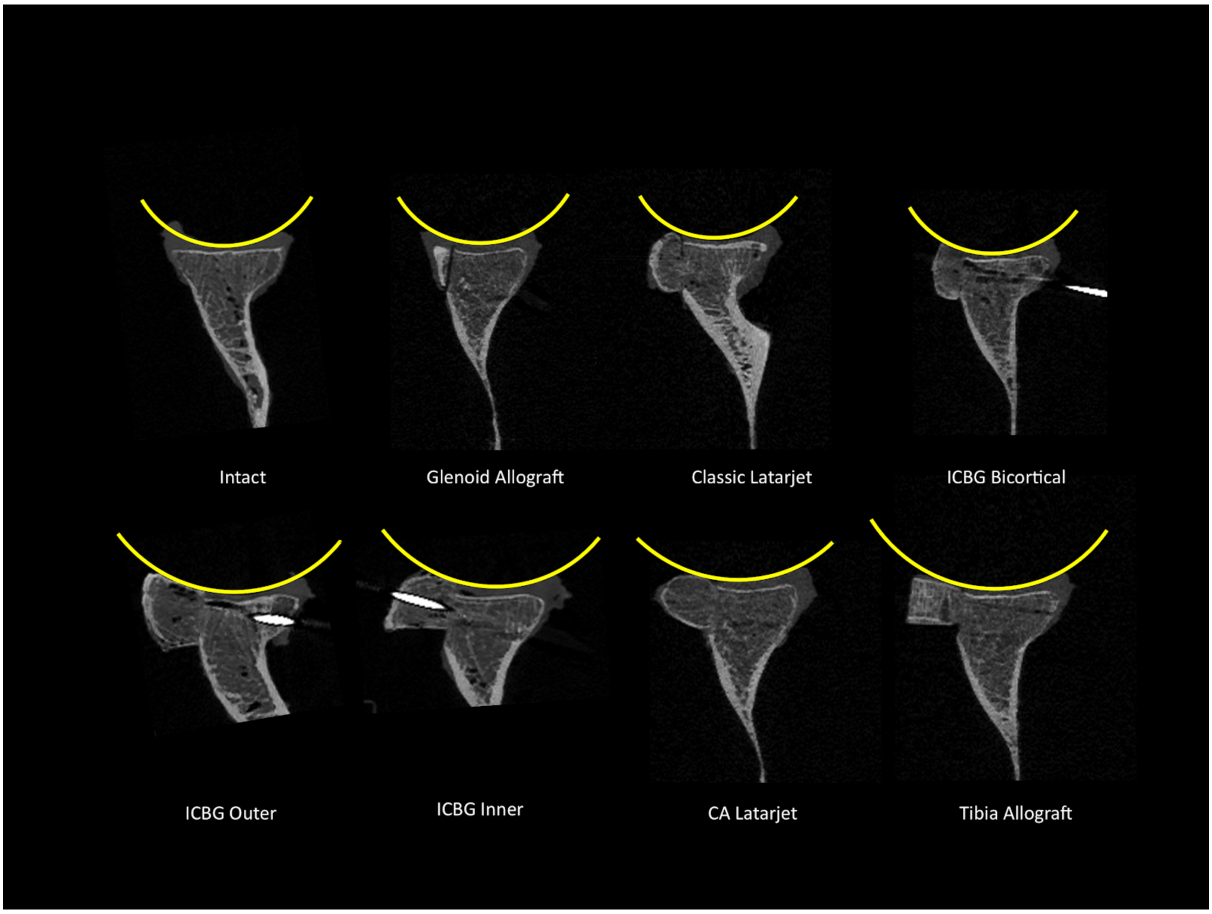

Figure 4.9

Illustrative example of axial curvature analysis for each condition on a left glenoid. Two-dimensional computed tomography axial slices of each condition at the widest anteroposterior glenoid level. Best to worst fit ordered from top left to bottom right.

Table 1. Bone and Soft-Tissue Window Reconstruction Measurements

	Intact (SD)	Def (SD)	%	Lat (SD)	%	CA Lat (SD)	%	Crest In (SD)	%	Crest Out (SD)	%	Crest Bic SD	%	Tibia (SD)	%	Glen (SD)	%
Width (bone)	28.3 (0.9)	20.0 (1.6)	70.8	25.3 (2.6)	89.3‡	31.8 (2.0)	112.5	32.2 (2.0)	113.9	32.6 (2.7)	115.3	26.1 (1.6)	92.4†	31.6 (1.1)	111.8	27.6* (2.0)	97.4*
Surface area (bone)	964.0 (58.8)	772.5 (45.4)	80.1	938.7 (70.0)	97.4†	1,081.3 (90.8)	112.2	1,051.3 (69.0)	109.1	1,040.2 (54.9)	107.9	898.0 (38.1)	93.2‡	1,045.9 (43.0)	108.5	958.6* (49.3)	99.4*
Articular step-off (bone)	0.00 (0.00)	NA	NA	1.9 (0.7)		1.4‡ (1.2)		1.9 (1.2)		2.5 (0.9)		2.3 (0.8)		0.4† (0.3)		−0.1* 0.3	
Depth (cartilage)	3.1 (0.7)	2.0 (0.5)	64.1	2.8 (0.3)	90.3	3.1* (0.8)	101.0*	3.3 (0.7)	107.0	3.7 (0.9)	120.8	2.9 (0.5)	92.9	3.0 (0.6)	98.9†	2.9 (0.3)	95.3‡
Curvature axial (cartilage)	0.039 (0.01)	NA	NA	0.042 (0.01)	108.7†	0.029 (0.004)	75.0	0.031 (0.01)	79.8	0.033 (0.01)	84.8	0.035 (0.002)	91.2‡	0.027 (0.003)	69.2	0.038* (0.003)	97.5*
Curvature coronal (cartilage)	0.040 (0.01)	NA	NA	0.022 (0.05)	55.9‡	0.060 (0.02)	151.7	0.015 (0.01)	37.1	0.002 (0.02)	5.8	0.016 (0.01)	40.0	0.041 (0.004)	115.0†	0.041* (0.003)	102.6*

NOTE. Overview glenoid parameters for the three-dimensional 3D "bone" and "cartilage"model reconstructions. The date show absolute measurements (standard deviation [SD]) and percentage of intact per condition.

CA Lat, congruent-arc Latarjet; Crest Bic, iliac crest bicortical; Crest In, iliac crest inner table; Crest Out, iliac crest outer table; Glen, glenoid allograft condition; Lat, Latarjet; Tibia, tibia allograft.

*Most accurate value per parameter.

†Second most accurate value by parameter.

‡Third most accurate value by parameter.

Table 4.1

Bone and Soft-tissue Window Reconstruction Measurements

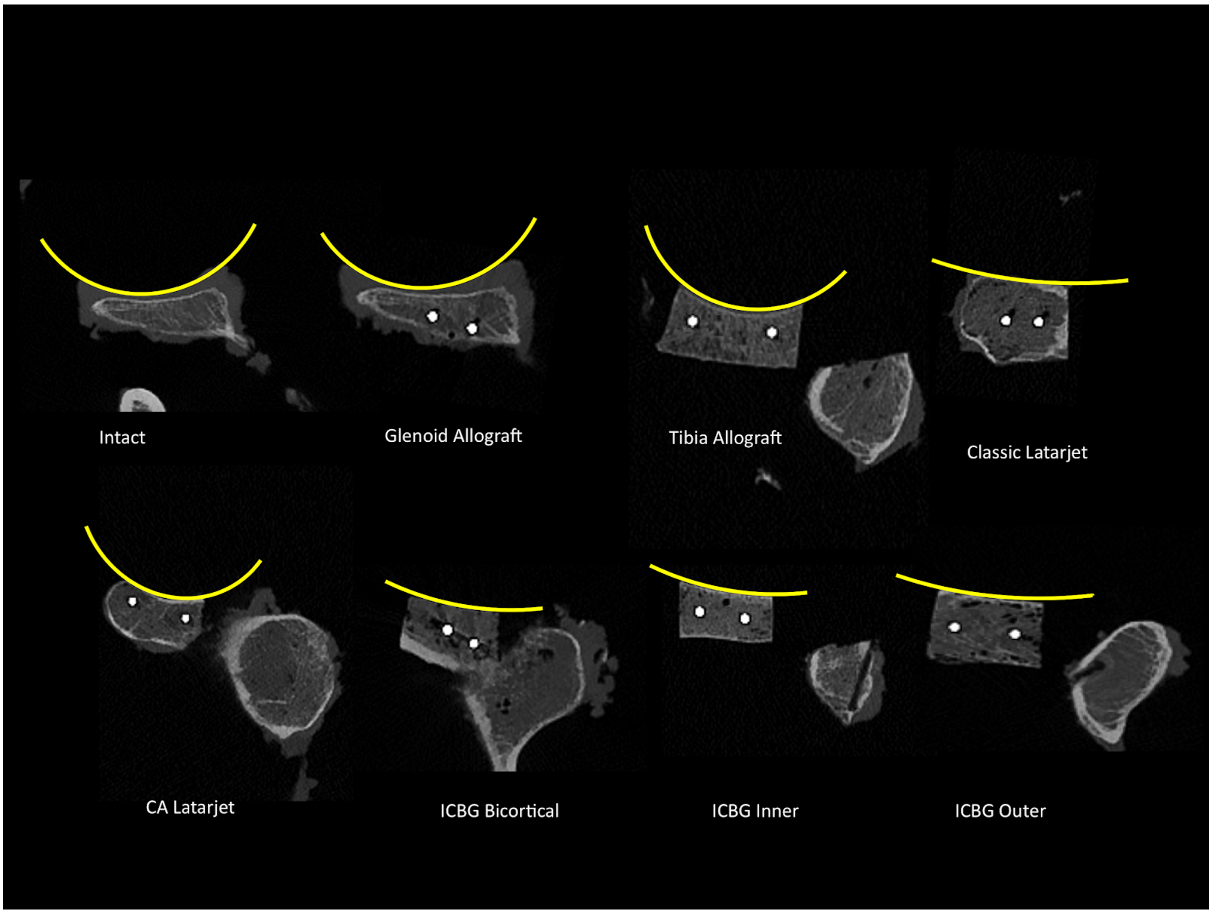

Figure 4.10
Illustrative example of coronal curvature analysis for each condition on a left glenoid. Two-dimensional computed tomography coronal slices of each condition 1 mm anterior to the osteotomy. Best to worst fit ordered from top left to bottom right.

4.2.4 Discussion

The purpose of this cadaveric study was to compare the morphology of grafts currently in use for reconstruction of glenoids with large anterior bone defects. The results of this study indicate that alternative bone grafts can perform as well as, or better than traditional coracoid transfer procedures in restoration of the bone-deficient glenoid. Not surprisingly, glenoid allografts were most accurate in the reconstitution of glenoid width, surface area, and both coronal and axial curvature. Additionally, glenoid allograft reconstruction resulted in the smallest intra-articular bony step-off. However, since fresh scapular allografts are not available in most treatment centers, other options should be considered. Classic Latarjet grafts performed well in width and surface area reconstruction and unexpectedly also adequately restored axial and coronal curvature. Coronal curvature did exhibit a wide range and variability, which may make the graft less suitable. Tibial allografts were able to closely match the coronal curvature with good depth restoration and minimal subchondral step-off but lacked axial curvature. The CA modified Latarjet failed to restore axial curvature and overcorrected coronal curvature. Iliac crest grafts overcorrected glenoid width and surface, except for the bicortical grafts. The iliac grafts exhibited a lack of curvature in the coronal plane and to a lesser extent the axial plane.

Tricortical and bicortical iliac crest autografts and tibial plafond and glenoid allografts are gaining in popularity as alternative graft sources to the traditional coracoid process for the restoration of glenoid bone loss in the setting of recurrent glenohumeral instability (Skendzel et al., 2011)(Taverna et al., 2014)(Kraus et al., 2014). Arguments favoring these techniques are the possibility of a less-invasive subscapularis-sparing all-arthroscopic approach, the lower risk of neurovascular injury, the customizable graft size, more accurate graft positioning and geometry, and less abrasive articular tissue reconstruction (Verborgt et al., 2013)(Wong et al., 2015). However, relatively little is known about the ideal surface geometry of grafts used for glenoid reconstruction. Conversely, graft geometry has to be weighed against concerns such as additional stabilization by the conjoint sling, allograft availability, allograft resorption, graft remodeling, coracoid harvest morbidity, and iliac crest graft harvest morbidity (Yamamoto et al., 2013)(Wellmann et al., 2012)(Di Giacomo et al., 2011)(Zhu et al., 2015)(Carbone et al., 2016)(Griesser et al., 2013)(Shah et al., 2012).

Incorrect articular reconstruction is associated with abnormal loading patterns, which may lead to early-onset osteoarthritis (Lädermann et al., 2011)(Gordins et al., 2015). Pressure mapping studies have shown a reduction in contact pressures with the CA Latarjet, tibial, and iliac crest grafts compared with classic coracoid grafts (Ghodadra et al., 2010)(Bhatia et al., 2013). This study aimed to compare graft width, surface area, depth, ROC in axial and coronal planes, and articular step-off of each graft type to the intact condition. From a morphological standpoint the glenoid allograft would intuitively be the first choice but is not universally available. The graft was included in the analysis both as a control for validation of our methods and as a viable graft option for certain centers. Glenoid bone surface area was overcorrected by the CA Latarjet, iliac crest inner, tibial, and iliac crest outer grafts and undercorrected by the iliac crest bicortical graft. The glenoid allograft and classic Latarjet grafts produced the smallest differences in surface area in comparison with the intact condition. However, the iliac crest, tibial, and glenoid grafts lend themselves to custom sizing, while the coracoid process is more restricted by anatomic dimensions. Nevertheless, Paladini et al. found adequate inferior glenoid circle “filling” after classic Latarjet procedure in a clinical study population with a mean defect size of 26% (Paladini et al., 2016). Noonan et al. performed a virtual reconstruction by Latarjet, CA Latarjet, iliac crest, and tibial plafond graft on clinical CTs of glenoids with 11% surface area loss. The results showed substantial overcorrection of surface area for all reconstructive options (mean, 119.5%; range, 111.1% to 130.1%), likely due to the smaller defect size (Noonan et al., 2014). Pressure mapping studies in a 30% bone loss cadaveric model reported an average of 73% of intact surface area restoration using the classic Latarjet technique versus 80% with the CA Latarjet, 82% with the tricortical iliac crest graft, and 101% with the tibial allograft (Ghodadra et al., 2010)(Bhatia et al., 2013). Montgomery et al. reported the restoration of defects up to 50% using CA Latarjet and 36% using classic Latarjet techniques (Montgomery et al., 2017). The differences with the findings of this study are partly explained by the larger defect size and the use of contoured grafts. Graft volume has been shown to adapt according to mechanobiological loading (Wolff’s law). The process of remodeling has been shown to revert the grafted glenoid to the original anatomical shape in clinical studies (Anderl et al., 2016). This has led some investigators to argue in favor of slight overcorrection, although prominent or loose hardware may become an issue after resorption (Willemot et al., 2019).

Glenoid depth is an indirect measure of glenohumeral constraint and a function of glenoid curvature and width Creation of the defect reduced depth by 36.9%. Maximal depth was restored most accurately by the CA Latarjet (101.0%), the tibial allograft (98.9%), and the glenoid allograft (95.3%). Mean axial curvature of the intact glenoid (0.039 mm1 or 25.64 mm ROC) was in agreement with the published literature by Soslowsky et al. and Zumstein et al. (Soslowsky et al. 1992)(Zumstein et al., 2014). Reconstruction by glenoid allograft proved most accurate with 97.5% of curvature restoration. All grafts, except for the classic Latarjet technique, resulted in a flatter glenoid in the AP plane than the intact condition. Tibial allograft and CA Latarjet performed the worst with 69.2% (P= .002) and 75.0% (P= .001). Noonan et al. reported on axial curvature analysis of various graft types. The authors reported convex curves for coracoid and tibia and wide variation for iliac crest grafts. However, the study compared injured glenoid curvature with graft curvature instead of overall reconstructed curvature (Noonan et al., 2014). Mean coronal curvature of the intact glenoid at the level of the defect (0.040 mm1 or 25.0 mm ROC) was also in agreement with previously published data (Zumstein et al., 2014)(Dehaan et al., 2013)(Armitage et al., 2011). Glenoid and tibial allografts were most successful at restoration of the curvature (102.6% and 115.0%). Decker et al., found very similar values for tibial bone curvature (23.0 mm ROC) but noticed a mismatch with the average glenoid curvature. However, the authors measured glenoid curvature at the center of the glenoid, not the site of injury (Decker et al., 2016). Dehaan et al. reported similar values (24.7 mm) to our study, whereas Noonan et al. found flatter tibial plafond curves (41.3 mm)(Dehaan et al., 2011)(Noonan et al., 2014). Iliac crest grafts were shown to have flatter curves in the coronal plane. The concave undersurface of the coracoid in the CA modified Latarjet was more curved (0.06 mm1 or 16.67 mm ROC) than the glenoid (P= .0015 and P= .049), while the classic Latarjet exhibited wide variation in the nature of the curve on its lateral face, ranging from concave to convex (SD= 0.05). Previous literature similarly report a more pronounced curvature of the coracoid undersurface, although a wide disparity exists among the studies (13.6, 24.0, and 60.3 mm) (Noonan et al., 2014)(Dehaan et al., 2013)(Armitage et al., 2011). Some of the difference may be attributed to the 3-point circle- fitting technique, which is more susceptible to error than the multiple point fitting. Furthermore, previously published data on glenoid geometry after reconstructive procedures have focused on subchondral bone surface, not on articular cartilaginous surface.

4.2.5 Limitations

Our study faced the known limitations of cadaver studies such as limited availability and advanced age of specimens. Moreover, graft geometry is only one aspect of glenoid reconstructive procedures. Graft SI and mediolateral position and tilt can also severely impact glenoid restoration. We chose to align the grafts flush with articular cartilage at the level of the inferior circle based on the senior author’s (O.V.) surgical preference and the available biomechanical data, although debate exists on ideal graft placement. Some investigators advocate placing grafts flush with the bone, giving priority to the continuity of the subchondral bone plate (Dumont et al., 2014) Furthermore, graft placement in this study reflected the ideal situation, which in reality may not always be achievable during surgery. Additionally, iliac and tibial graft size was selected based on literature review and current surgical practice of the senior author but may vary from case to case and surgeon to surgeon in reality. Similar to Noonan et al., we found a great variability of geometry within some of the grafts types. Glenoid allografts and tibial allografts had narrow SD, but coracoid and iliac crest grafts tended to exhibit a wider variability in several parameters. Imaging studies cannot take into account the mechanical properties of the tissues, which may influence joint congruity and congruence after loading. Lastly, cadaveric studies such as this one cannot anticipate remodeling and cartilage degeneration after bone grafting occurs. However, the immediate postoperative situation is believed to be of value for the prediction of early-onset arthrosis.

4.2.6 Conclusions

Overall, glenoid allografts most accurately restored articular geometry. Alternative grafts provided restoration of some parameters but not others. Classic Latarjet performed well in axial and coronal curvature on average but exhibited large variability. Tibial allograft produced the poorest results in axial curvature, despite excellent coronal curvature reconstruction. The CA Latarjet did not restore the axial curvature accurately and overcorrected coronal curvature. Graft geometry must be weighed against availability, morbidity, and the role of additional stabilizers.

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Chapter 5: Complications of Bone Block Procedures

"Shit Happens! Mal bist du die Taube, mal bist du das Denkmal."

Dr. E. Von Hirschhausen

Overview

This chapter deals with the complications of anterior glenoid bone grafting procedures. Overall risk, recurrence, arthropathy, as well as graft-specific, harvesting, and fixation complications are discussed in detail. Our publications concerning the revision of failed Bristow-Latarjet procedures and the biomechanical fixation methods of grafts are also presented here.

5.1 Introduction

5.1.1 Failures and Complications

The resurgence of bone grafting procedures represents a pivotal evolution in our understanding and treatment of traumatic anterior shoulder instability (Boileau et al., 2006)(Burkhart and de Beer, 2000)(Montgomery et al., 2005). However, despite the significant reduction in recurrence rates and good clinical outcomes, concerns about the risks of anterior glenoid bone grafting procedures have featured prominently in the literature (Young et al., 1991)(Griesser et al., 2013)(Gupta et al., 2015). Complications range from relatively minor risks such as postoperative hematoma and infection to major long-term problems such as early-onset arthropathy and neurovascular injury. Griesser and colleagues reviewed the literature and reported an overall complication rate of 30%, with a 7% reoperation rate after Bristow-Latarjet (Griesser et al., 2013). A later and larger systematic review by Longo et al., reported an overall rate of 15% complications for coracoid transfers and 17.2% for Eden-Hybbinette procedures (Longo et al., 2014).

Recurrence is often reported in the same category as complications, although the term "complication" typically refers to a secondary or additional disease process, not merely the reversion to a pre-existing state (Miller-Keane Encyclopedia and Dictionary, 2003). Nevertheless, renewed instability may be the result of a complication (i.e. graft malposition) or may indicate a failure of the primary procedure. Recurrence may also be the result of independent new trauma. The risk of recurrence after glenoid bone grafting is discussed in more depth below. Degenerative glenohumeral changes have long been associated with shoulder instability. The exact cause-effect relationship between dislocation and osteo-arthritis has been the subject of much scientific attention. The exceptional long-term work done by Hovelius and colleagues has shed light on the natural history of osteo-arthritis in unstable shoulder joints and the effect of Bristow type procedures, yet the long-term results of more recent anterior bone grafting procedures is still unknown (Gordins et al., 2015)(Hovelius et al., 2016). Post-stabilization arthropathy is explored more thoroughly in a dedicated paragraph.

Postoperative infection rates are typically divided in superficial and deep, and the incidence is estimated to be around 1-6% in the Bristow-Latarjet literature (Butt et al., 2012)(Griesser et al., 2014)(Metais et al., 2016)(Shah et al., 2017). Treatment usually consists of irrigation, debridement and appropriate antibiotic therapy, although removal of hardware may sometimes be necessary in refractory cases. Infection has been associated with failure of bony union and recurrence (Domos et al., 2017). Preventative measures are in agreement with the traditional prophylactic and aseptic precautions prescribed for most orthopedic procedures (Shah et al., 2015)(Domos et al., 2017). Infections may sometimes coincide with postoperative hematoma formation. Bleeding complications have been reported in less than 1% of operations and are typically managed conservatively. The prevention of postoperative hematomas is directly related to peroperative haemostasis, especially bleeding from the osteotomy site. In rare cases of large or expanding postoperative bleeds, surgical drainage may be necessary (Butt et al., 2012)(Griesser et al., 2013)(Gupta et al., 2015).

The incidence of graft non-union is estimated around 9%, while resorption of the graft is seen in 59.5% of Bristow-Latarjet cases (Griesser et al., 2014)(Di Giacomo et al., 2011). The type, position and fixation of the selected graft is believed to play an important role in the prevention of recurrence, non-union and resorption. The intricacies of graft-specific complications are discussed in detail below. Similar to most stabilizing procedures, anterior glenoid grafting is associated with a risk of stiffness. Loss of range of motion after shoulder stabilization may be caused by postoperative capsulitis, but is more frequently the result of subscapularis injury (Domos et al., 2017). Immediate postoperative loss of motion may be caused by bony impingement on proud hardware or graft malpositioning (Willemot et al., 2019). Special attention is given in this chapter to the side effects of graft harvesting. The risk of neurovascular injury and the influence of non-anatomic transfers such as the Bristow-Latarjet are explored further in the following paragraphs.

Hardware complications constitute 35% of indications for revision surgery after Bristow-Latarjet. Often hardware is simply removed, yet certain cases require further bony stabilizing. Lunn and colleagues reported good or excellent results in 79% of their 46 patients after performing ICBG stabilization for failed Latarjet. The authors noted only 1 recurrence and only 7% subjective instability in their population after 9 years (Lunn et al., 2008). Similarly, Giannakos et al., reported satisfactory results in 67% of patients, yet a persistence of apprehension in 42% after 28.8 months (Giannakos et al., 2017). These results indicate that free bone grafts have the potential of stabilizing shoulders where the biomechanically superior coracoid transfer procedures have failed. However, the distinction between overt dislocation (macro-instability) and subtle apprehension (micro-instability) can be a confounding factor in the evaluation of results. The divergence in results may also be the result of faulty indication during the index procedure. Domos and colleagues outlined several contra-indications in otherwise intuitive candidates for Bristow-Latarjet, and by extension anterior glenoid bone grafting procedures. The authors warned against the use of coracoid transfers in patients over 50 years old, patients presenting with massive cuff tears, voluntary dislocators, uncontrolled epileptic patients, unstable shoulder prostheses, and patients suffering from painful micro-instability. Bristow-Latarjet procedures have a proven record of unpredictable or poor outcomes in these patients (Domos et al., 2017). We performed our own analysis of failures in Bristow-Latarjet which is presented below.

5.1.2 Retrospective Analysis of Failed Bristow-Latarjet

A retrospective analysis was performed of all patients who required open revision surgery after either a Bristow or a Latarjet procedure for recurrent anterior shoulder instability. The patients were drawn from the institutions' (AZ Monica en Terbrugen Schoudergroep) databases between January 2006 and January 2017. After the exclusion of open procedures involving drainage due to hematoma or infection, a total of 29 cases from two treatment centers were eligible for further retrospective study. Three patients had incomplete files or were lost to follow-up. The remaining cohort consisted of 20 males and 6 females. The mean age at the time of the index procedure was 29.4 years (± 6.6). Clinical and operative charts were reviewed to assess primary indication, graft and hardware specifications, their activity level at time of revision according to the Walch-Duplay score, as well as type and timing of the revision procedure. Pre-operative radiographic images, classic radiographs and computed tomography (CT), were examined in all cases to assess graft and hardware position, graft non-union, graft migration or loosening, graft fracture or resorption, and glenohumeral arthritic changes according to the Samilson-Prieto classification. Radiographic changes were recorded as described previously (Young et al., 2011)(Hovelius et al., 2012). Combining the clinical and radiographic data, the most likely failure mechanism was determined in each case. A postoperative visit or follow-up telephone interview was conducted to assess Subjective Shoulder Score (SSS), Western Ontario Shoulder Instability index (WOSI), type and number of recurrences if any and return to sports. Radiographic follow-up was present until one year after the revision procedure in all patients. Radiographs were scored according to the Samilson-Prieto classification. Statistical subgroup comparison was done with the help of the SPSS statistical software package (IBM SPSS Statistics, IBM, Armonk, NY, USA). Ethical Review Board approval was granted to conduct this retrospective study (EC/2014/0060).

5.1.3 Results

The initial anterior bone grafting procedure was a Bristow type procedure in 5 patients, and a Latarjet type procedure in 21. The activity level was competitive in 30.7%, leisure in 38.4% and not practicing in 23.1%. The type of activity was high risk in 3 cases, with contact in 7 and no risk in 8. The mean time between the primary and revision procedure was 3.11 years (± 2.8). Four types of failures were seen. (Fig. 5.1) A summary of each case is given in table

5.1. Graft non-union was diagnosed as the cause of failure in 11 cases (42.3%). Mean time between primary and revision procedure was 2.2 years (± 1.4). Evidence of graft non-union culminating in renewed instability in the absence of significant trauma was present in all 11 cases. In seven patients, construct failure with hardware breakage and graft displacement occurred before revision. In the remaining 4 patients, revision surgery was performed before hardware failure. CT evaluation showing screw loosening and glenoid cyst formation was observed in 6 of the 11 patients revised for non-union. Unicortical screw fixation of the graft was noticed in nearly half of the non-union cases (5/11) (Fig. 5.2) Two cases were associated with uncontrolled epilepsy. Graft resorption was the main failure mechanism in 6 patients (23.1%). (Figure 5.3) The mean time between primary and revision procedure was 5.3 years (±2.3). Resorption was undiagnosed in all cases until recurrent instability prompted further imaging.

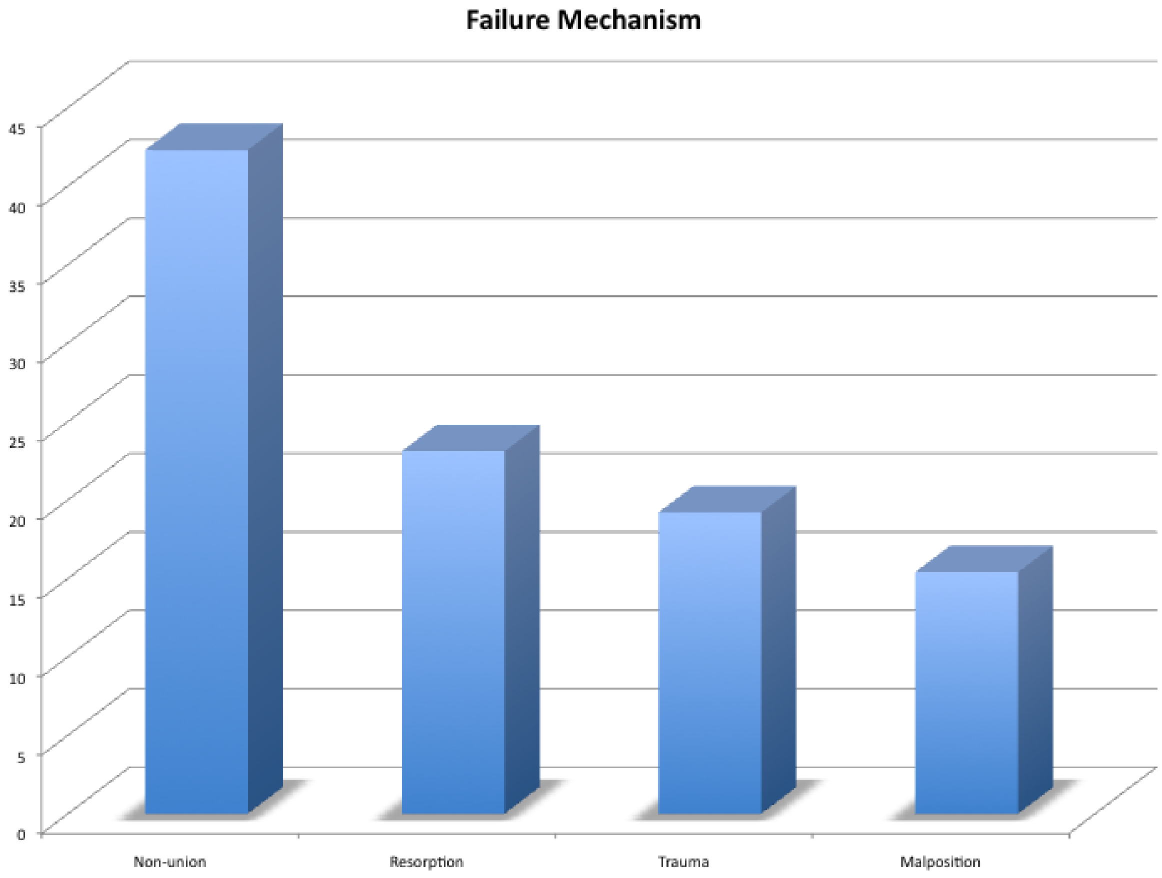

Figure 5.1
The bar chart depicts the distribution of cases according to failure mechanism.

Malposition of the graft or hardware was the deemed to be the cause of failure in four cases (15.4%). Mean time between primary and revision procedure was 2.3 years (±2.7). In three

cases the graft was placed too laterally on the glenoid neck, causing anterior impingement and hardware irritation. (Figure 5.4) One patient presented with recurrent dislocation due to an excessively inferior graft position. (Figure 5.5.) The patient complained of antero-superior instability with occasional full dislocation requiring reduction in the emergency room. Grafts positioned too medially or superiorly were not observed in this cohort.
Finally, graft fracture and graft migration were observed in 5 cases (19.2%).
The mean time between primary and revision procedure was on average 2.9 years (±4.5). Failure following major trauma to the operated shoulder without indication of impending hardware loosening or fracture was observed in two cases. In two other cases, graft fracture was believed to originate from peroperative graft handling. One incident was related to an uncontrolled epileptic insult.

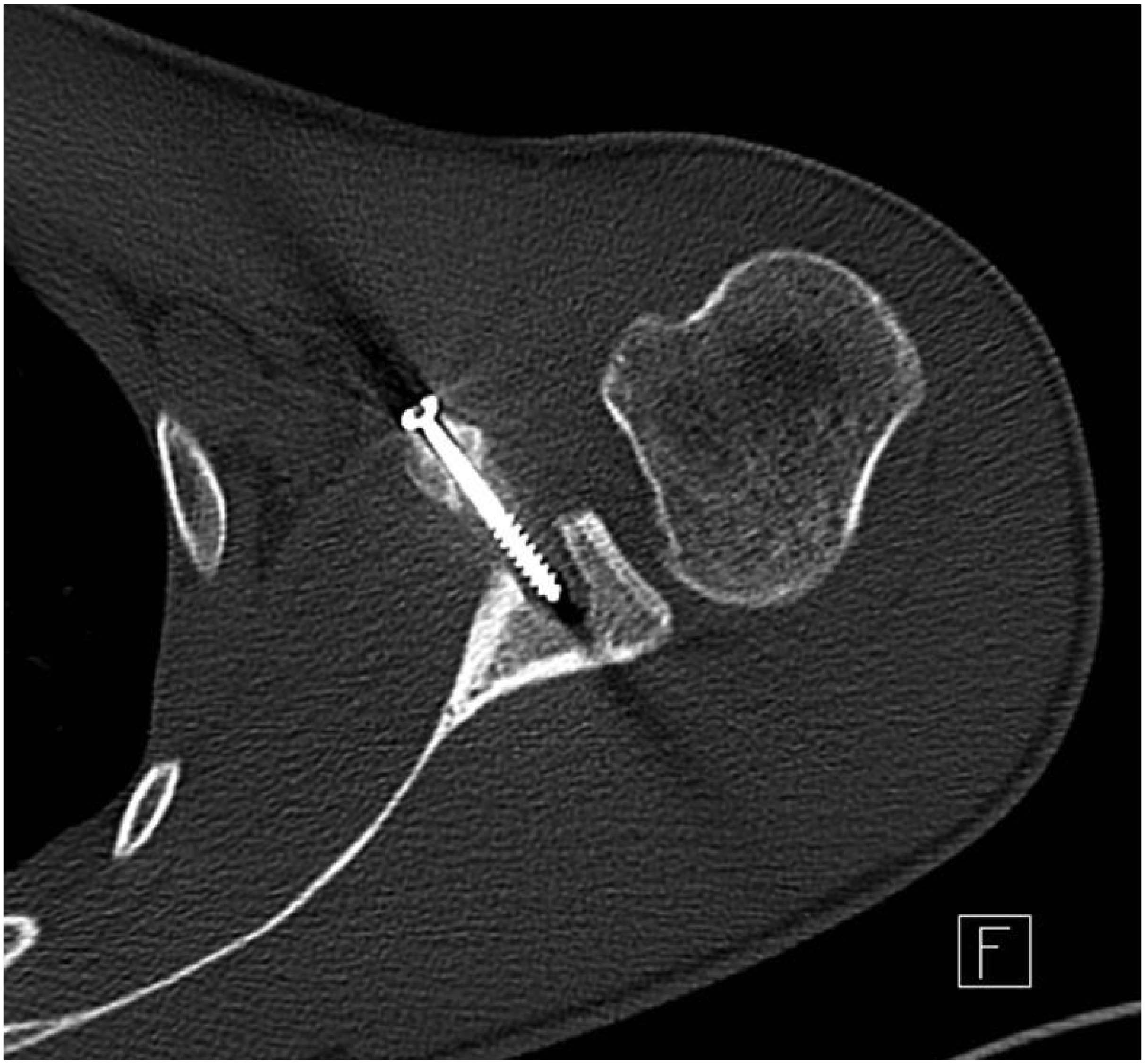

Figure 5.2
Non-union with hardware loosening. Axial CT slice of a left shoulder showing graft non-union and loosening around a unicortical screw in the glenoid metaphysis

The time between index procedure and revision was significantly greater in the resorption group compared to the non-union ($p<0.001$), malpositioning ($p=0.04$) and fracture group ($p=0.04$). The revision procedure consisted of a structural iliac crest bone graft procedure (Eden-Hybinette) in 76.9% (20 cases), re-implantation of the original coracoid graft with an iliac crest bone graft or autologous cancellous bone grafts in 11.5% (3 cases), and repositioning of the original graft in 11.5% (3 cases)

Figure 5.3
Graft resorption. Axial CT slice of a left shoulder showing complete resorption of the graft around the screwhead

Mean follow-up time was 43.7 months (± 27.7 months). Mean Subjective Shoulder Score was 60.2% (±19.6). WOSI scores averaged 709.3 points (± 412.5). Three patients reported a persistent feeling of instability or subluxations but none of the patients reported any recurrences. Nine patients (46.1%) returned to their pre-revision level of sport.
Fourteen (53.8%) patients demonstrated evidence of degenerative arthritis on follow-up radiograph, 7 patients were scored as mild (grade 1), 4 as moderate (grade 2) and 3 as severe (grade 3) glenohumeral arthritic changes. Nine patients demonstrated evolutive radiographic changes (34.6%). This constituted an increase of 1 grade point for 6 patients, 2 grade points for 1 patient and 3 grade points for 2 patients compared to the pre-revision

imaging. The remaining 17 patients did not show any evolving degenerative changes on radiography.

Figure 5.4
Lateral malposition. Axial CT slice of a left shoulder showing an excessively lateral coracoid graft with intra-articular screw prominence in conflict with the humeral head

5.1.4 Discussion

The Bristow and Latarjet coracoid transfer procedures have a proven record of success in the treatment of recurrent shoulder instability (Allain et al., 1998)(Hovelius et al., 2012)(Mizuno et al., 2014). However, in tandem with the recent gain in popularity, a rise in complications has been observed. Much remains unclear about the management of a failed Bristow or Latarjet procedure. In previous studies, Castagna et al. have investigated the role of arthroscopy, while Lunn et al. discussed open revision using an iliac crest grafting procedure (Castagna et al., 2011)(Lunn et al., 2008). In contrast, recent studies have scrutinized Bristow-Latarjet procedures in order to better understand the underlying failure mechanism (Hovelius et al., 2012)(Gupta et al., 2012). In a similar manner, we have attempted to map these processes by reconstructing the clinical and radiographic evidence preceding the failure. Most importantly, our findings suggest a role for graft non-union as a causative factor in the lead up to hardware failure and recurrence.

Fibrous Union

Graft fibrous or non-union is a well-known phenomenon after Bristow-Latarjet type procedures. Two recent review studies found 9.4% and 10.1% non-union rates respectively (Griesser et al., 2013)(Shah et al., 2015). The actual rate may be higher but remains undetected in the absence of a dedicated postoperative CT scan protocol. Recent studies have reported significantly higher healing rates after arthroscopic Bristow-Latarjet compared to the traditional open method (Kordasiewicz et al., 2018). Generally, fibrous union is deemed an incidental and innocent finding, rarely requiring attention (Butt et al., 2012)(Gupta et al., 2015)(Domos et al., 2017). However, in this study we found that the majority of open revisions were related to graft non-union. Hardware failure is not often linked to graft pseudarthrosis in the available literature, yet in this longitudinal case-by-case study, we have found arguments to support that hardware failure may be the result of long-standing non-union. In close to half of the hardware failures, clear signs of loosening around the screws and glenoid cyst formation were observed before final hardware failure and construct collapse. The majority of these cases were not associated with significant new trauma. Therefore, we believe that graft non-union may not be as inconsequential as previously thought. Long-lasting fibrous union may eventually culminate in hardware or graft failure in the active patient due to loosening and material fatigue. Besides patient factors such as age, smoking and immunological status, surgical technical aspects play an important role (Boileau et al, 2014). Similarly to Cassagnaud et al., our study found a surprisingly high rate of unicortical screw fixation (41.2%) in the non-union group which may play an etiological role (Cassagnaud et al., 2003). Thorough decortication of both the graft and recipient site as well as adequate compression and immobilization of the graft are believed to be crucial although much remains unknown about this topic (Gupta et al., 2015). Patients in our cohort were treated either by debridement of the original graft site and anterior glenoid rim and substitution with a tricortical iliac crest graft except in two cases where the graft was reimplanted with the aid of cancellous bone grafts.

Resorption

As described by Di Giacomo et al., partial graft resorption is frequently observed after coracoid transplantation (Di Giacomo et al., 2011). The inverse relationship between preoperative glenoid bone loss and graft osteolysis supports the role of mechanotransduction in this process of remodeling (Di Giacomo et al., 2014). Although some argue that the conjoint sling effect and capsular reinforcement provide ample stability in the case of graft resorption (Gupta et al., 2015), our study contained six patients requiring Eden-Hybinette reconstruction due to recurrent instability after complete graft osteolysis. Our analysis also indicated that the time between index procedure and revision, and therefore indirectly the time to failure, was significantly greater in the cases of resorption compared to the other failure mechanisms.

Graft Position

Ideal graft position is not completely understood. Saito and colleagues suggested placing the graft between 2:30 and 4:30 based on the location of the average glenoid fracture on a right scapula (Saito et al., 2005). Similarly, Hovelius et al. demonstrated an association between grafts placed above the equator and an increased recurrence in their series (Hovelius et al., 1983)(Hovelius et al., 2012). However, none of the patients in our series presented with this type of malpositioning. The study contained one patient with recurrence due to inferior graft placement, allowing antero-superior instability. Previous biomechanical research has shown the importance of sagittal plane graft position in restoring glenohumeral stability (Willemot et al., 2015)(Nourissat et al., 2014). Different harvesting strategies can be used depending on whether the procedure is intended as a restoration of the glenoid bone loss or to promote healing of the conjoint tendon transfer or both. Typically, a larger graft is harvested for articular reconstructive purposes and a smaller graft, usually only the coracoid tip, for tendon transfer (Mizuno et al., 2014)(Hovelius et al., 2012)(Tang et al., 2018). However, some have modified the Bristow procedure to include a large on-end graft (Doursounian et al., 2009). Burkhart et al. advocated placing the graft's inferior cortex flush with the articular surface due to concerns over the coracoid's incongruent lateral surface and size (Burkhart and De Beer, 2000). The current literature has not been able to identify superior clinical outcomes of one technique over another. Conversely, recent research has shown that the classic Latarjet orientation can adequately restore the glenoid articular bone stock in cases with more than 20% bone loss (Paladini et al., 2016).

It is generally agreed that the graft should be placed flush or slightly medial to the glenoid cartilage. Excessive medial position is thought to cause recurrence due to insufficient reconstruction of the glenoid articular constraint (Allain et al., 1998)(Mizuno et al., 2014)(Hovelius et al., 2012)(Allain et al., 1998)(Lunn et al., 2009)(Metais et al., 2016). In cases without major bone loss, this may not be of equal importance, when the coracoid transfer procedure mainly functions as a dynamic sling, similar to the soft tissue Bristow procedure or conjoint tendon-only transfer (Kephart et al., 2014). Excessive lateral position occurs in up to 53% percent of cases in some studies and has been correlated with early joint arthritis (Allain et al., 1998)(Hovelius et al., 2012)(Lädermann et al., 2013). Our study included three patients with excessively lateral graft position and acute postoperative symptoms. Revision surgery consisted of medialization of the graft in all cases.

Figure 5.5
Inferior malpositioning. Coronal CT slice of a left shoulder showing a small graft placed inferiorly on the glenoid rim

Fracture and Traumatic Graft Migration
Graft fracture and graft migration were observed in 19.2% of cases. Failure following major trauma to the operated shoulder without indication of impending hardware loosening or fracture was observed in three cases (11.5%). (Fig. 5.6) Graft fracture was believed to originate from peroperative graft handling in two other cases. One incident was related to uncontrolled epileptic insults. All cases were treated by tricortical iliac crest grafting.

Figure 5.6
Graft fracture. Anteroposterior radiograph of the left shoulder showing graft fracture and displacement with concomitant screw pull-out

Clinical outcome

The Eden-Hybbinette-type anterior glenoid bone grafting procedures have been used in the stabilization of shoulder instability for over a hundred years. Although the procedure temporarily fell out of favour after being linked to early-onset shoulder arthritis, it is a valid contemporary solution for both primary and revision cases of recurring anterior shoulder instability (Lunn et al., 2008)(Steffen et al., 2013)(Giannakos et al., 2017). Our study demonstrates that stability could be restored in most patients, yet with significantly lower shoulder scores than those reported in the literature after primary bone block stabilization (Allain et al., 1998)(Mizuno et al., 2013)(Taverna et al., 2014)(Kraus et al., 2014). Less than half of the athletic patients in our patient cohort were able to regain their pre-injury activity level. Additionally, about half of the patients exhibit mild or worse signs of glenohumeral osteo-arthritis on radiography. Three patients demonstrated severe arthritic changes on the final radiography. A slight deterioration of osteo-arthritis was noted in the follow-up radiographic exams, however this study is not suited to answer the question whether the functional and degenerative changes are due to the recurrent trauma, the multiple surgical procedures or the type of procedures.

Limitations

This study exhibits some of the classical shortcomings of a multicentric retrospective analysis such as patient and procedural heterogeneity, loss to follow up and incomplete datasets.

Table 5.1

Table 1 Summary overview of case series characteristics

No.	Age (years)	Sex	First	No. of dislocations before revision surgery	Bone loss	Nicotine	Pre-bone block surgery	Type of bone block surgery	Recurrence	Mechanism	Revision
1	28	Male	Fall	20	None	Yes	Open Bankart	Bristow	Fall down stairs	Resorption of bone block	ICBG
2	30	Male	Fall from horse	60	Not significant Hill-Sachs	Yes	Open Bankart	Bristow	Collision with wall	Renewed trauma	ICBG
3	29	Male	Fall	15	Small bony Bankart	No	None	Bristow	Perioperative graft fracture and postoperative trauma	Fractured and migrated graft	ICBG
4	33	Female	Fall on ice	2	Not significant Hill-Sachs	No	Open Bankart	Latarjet	Spontaneous subluxation, full dislocation after fall	Resorption of bone block	ICBG
5	28	Male	Epileptic insult	100	Significant Hill-Sachs	No	None	Latarjet	New epileptic insult	Non-union with cyst formation followed by hardware fail	ICBG
6	26	Male	Kayaking	1	Significant Hill-Sachs	No	None	Latarjet	Spontaneous	Non-union followed by hardware fail	ICBG
7	19	Male	Motocross	3	Not significant Hill-Sachs	Yes	Open Bankart	Latarjet	Motorcross Accident	Non-union with cyst formation followed by hardware fail	Refixation graft plus ICBG
8	35	Male	Motorcross	0	Significant bony Bankart	No	None	Latarjet	Incident during push-ups 3 weeks postop	Non-union with cyst formation followed by hardware fail	Revision pseudarthrosis with cancellous bone grafts
9	35	Male	Surfing	1	Significant Hill-Sachs	Yes	None	Bristow	Subluxation spontaneous	Painful non-union with in-stability	ICBG plus coracoid reinsertion
10	32	Male	Weightlifting	1	Significant bony Bankart	Yes	None	Latarjet	Forced internal rotation during police intervention	Extruded hardware and graft failure	ICBG
11	33	Male	Boxing	10	Small bony Bankart	Yes	None	Latarjet	Early return to sports	Painful non-union with in-stability	ICBG
12	17	Male	Fall	15	Small bony Bankart	Yes	None	Latarjet	Spontaneous	Non-union with cyst formation followed by hardware fail	ICBG
13	22	Male	Squash	12	Small bony Bankart	No	None	Latarjet	Incident during paddling	Non-union with cyst formation followed by hardware fail	ICBG
14	42	Female	Volleyball	5	None	No	None	Bristow	Spontaneous	Inferior graft malposition	ICBG above coracoid graft
15	34	Female	Fall in bathroom	1	Small bony Bankart	No	None	Latarjet	After screw removal	Resorption	ICBG
16	30	Male	Soccer	100	Small bony Bankart and Hill-Sachs	Yes	None	Latarjet	None	Excessive lateral position	Repositioning
17	25	Male	Epileptic Insult	3	Small bony Bankart and significant Hill-Sachs lesion	No	None	Latarjet	New epileptic insult	Graft fracture and hardware failure	ICBG
18	27	Male	Swimming	20	Significant bony Bankart	No	None	Latarjet	Lifting arm	Resorption	ICBG
19	21	Female	Judo	5	Significant Hill-Sachs	No	Capsular plication	Latarjet	Dislocation during contact sports	Resorption	ICBG
20	39	Male	Fall from height	1	Small bony Bankart and Hill-Sachs lesion	No	None	Latarjet	Posterior subluxation	Posterior instability due to lateral graft position	Graft medialization

Table 1 (continued)

No.	Age (years)	Sex	First	No. of dislocations before revision surgery	Bone loss	Nicotine	Pre-bone block surgery	Type of bone block surgery	Recurrence	Mechanism	Revision
21	36	Female	Fall	10	Significant bony Bankart and Hill-Sachs	No	None	Latarjet	Pain and instability	Non-union with cyst formation followed by hardware fail	ICBG
22	18	Male	Fall from stairs	100	Significant Hill-Sachs and ALPSA	No	None	Latarjet	Pain and instability	Graft and screw fracture due to new trauma	ICBG
23	26	Male	Epilepsy	100	Significant Hill-Sachs	Yes	None	Latarjet	Instability after epileptic insult	Non-union followed by hardware fail after seizure	ICBG
24	36	Female	Ehler-Danlos	3	Significant Hill-Sachs	No	None	Latarjet	Spontaneous Pain	Lateral graft position	ICBG
25	24	Male	Soccer accident	10–15	Small Bankart lesion	Yes	None	Latarjet	Pain and instability	Resorption	ICBG
26	25	Male	Fall	3	Small Bankart and Hill-Sachs lesion	No	None	Latarjet	Pain and instability	Graft non-union	ICBG

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5.1.5 Conclusion

Graft non-union resulting in recurrent instability was the main indication for open revision surgery after Bristow or Latarjet procedure in this retrospective case series. The paper suggests an important role for fibrous union or non-union in the lead-up to hardware breakage and construct failure. Other indications for open revision surgery were graft resorption, malpositioning and fracture. Revision surgery consisted of a structural iliac crest bone graft in the majority of cases. Clinical outcomes reflect the complexity of treating failed anterior bone graft procedures in shoulder instability. Stability was achieved in most cases, albeit at a functional cost.

5.2 Recurrence

5.2.1 Coracoid transfer procedures

One of the main drivers behind the success of the Bristow-Latarjet procedures has been the remarkable drop in recurrence rates compared to classic soft-tissue repairs. Allain et al. reported only 1 subluxation in 95 patients at 14.3 years follow-up (Allain et al., 1998). In another study, Mizuno and colleagues reported 5.9% recurrence at a mean follow-up of 20 years, using the Walch modification of the Latarjet procedure. The majority were redislocations, and only 8% exhibited subluxations (Mizuno et al., 2014). Hovelius found a rate of 5% redislocation and 13% subluxations after 6-17 years, using his modification of the Bristow procedure (Hovelius et al., 2012). A large systematic review similarly reported a recurrence rates of 7.5% (range 0 - 19%) across 37 studies, totalling 2459 shoulders (Longo et al., 2014). More recently, a systematic review selectively looking at studies with more than 10 years follow-up reported 8.5% recurrence, of which 3.2% were subluxations, at 16.6 years (Hurley et al., 2017). Recurrent dislocation is typically attributed to incorrect patient selection, complications (i.e. infection) or technical errors (Domos et al., 2017). However, sufficiently energetic renewed trauma may also be a reason for failure (Shah et al., 2012). Technical errors include suboptimal graft position, cursory surgical technique and faulty fixation devices. These aspects are discussed below.

The congruent-arc modification of the Latarjet procedure, which involves a 90° rotation around its axis to supply a larger and more congruous surface area for articular reconstruction, has shown similar good results (deBeer et al., 2010). Despite the legitimate concerns regarding fixation strength of the constructs, there are no examples of direct comparisons between both techniques in regards to recurrence rates in the literature (Montgomery et al., 2017). Likewise, arthroscopic techniques have shown promising results. A systematic review reported an overall recurrence rate of 0-8.3% across 7 studies with a variety of techniques. Unfortunately, most of these have a limited follow-up of less than 2 years (Saliken and Boileau, 2017). The longest follow-up in literature in the domain of arthroscopic Latarjet was published by Dumont and colleagues. The study reported only one subluxation in 64 shoulders after a mean of 5 years using the technique pioneered by Lafosse (Dumont et al., 2014). Interestingly, in contrast to the open Latarjet, this specific technique does not include a capsular repair. Other arthroscopic techniques such as the modified Bristow promoted by Boileau do include a soft-tissue repair after completion of the coracoid transfer (Boileau et al., 2015). Whether or not capsular repair has an influence on recurrence, and more particularly micro-instability, is the subject of ongoing debate. Biomechanical evidence is contradictory on the subject (Schulze-Borges et al., 2013)(Kleiner et al., 2016). A landmark clinical study by Hovelius and colleagues did, however, report a reduction in instability from 18% to 4% after the addition of a horizontal capsular shift to the open Bristow technique (Hovelius et al., 2012).

Studies have not indicated a greater risk of recurrent instability in contact athletes compared to non-contact athletes (Paulino Pereira et al., 2018). The authors attributed these contra-intuitive findings to higher proprioception and stricter physiotherapy follow-up in collision athletes. However, the absence of uniformly accepted definitions of what constitutes contact and collision athletes complicates the interpretation of the results. Nevertheless, the Bristow-Latarjet procedure is typically preferred in high risk athletes due to the biomechanically superior results compared to free bone grafting. High return to sports rates have been reported with coracoid transfer procedures, despite a significant incidence of degenerative changes (Beranger et al., 2016)(Lebus et al., 2017)(Neyton et al., 2017).

5.2.2 Free bone grafts

Recent studies examining the recurrence rates of open iliac crest bone grafting procedures have been reassuring. Auffarth and colleagues reported no recurrences after 6 years in their 47 patients treated with J-bone grafting (Auffarth et al., 2008). Steffen and Hertel reported only 1 redislocation and 3 apprehensives out of 43 patients treated with anterior glenoid rim reconstruction (Steffen and Hertel, 2013). Warner didn't report any dislocations or subluxations at 33 months postoperatively (Warner et al., 2006). Similarly, Scheibel et al., reported no recurrences in an open iliac crest based reconstructive technique (Scheibel et al., 2008). However, the authors did warn about the detrimental effect of subscapularis takedown on the quality of the muscle. The risk of subscapularis fatty degeneration is discussed in more detail further on in this chapter. The reported results are a significant improvement compared to the historical data, which tends to skew the findings of systematic reviews. Longo et al., reported an overall recurrence rate of 9.8% in their review paper (Longo et al., 2014).

Arthroscopic iliac crest grafting techniques have only relatively recently been described. Anderl and colleagues reported no recurrences at 2 years using an all-arthroscopic J-bone technique (Anderl et al., 2016). Likewise Taverna and colleagues, as well as Scheibel et al., reported no recurrence after a minimum of two years using a an arthroscopic tricortical iliac crest grafting technique (Taverna et al., 2018)(Kraus et al., 2014). An important feature of most, if not all, ICBG techniques, is the incorporation of a capsular repair step after completion of the bone grafting step. It should be noted however that most of these studies represent only short to mid-term follow-up. Concerning the use of tibial allograft the data becomes even more rarified. Provencher and colleagues found no recurrences in the 27 patients treated with distal tibia allograft after a mean of 45 months. Interestingly, the authors mention an inconsistent approach to capsular repair, only performing it when “available”. This however, did not seem to affect recurrence risk (Provencher et al., 2017). In another study by the same group, comparing 50 patients with distal tibia allograft reconstructions to a matched cohort of Latarjet patients, the authors noted only 1 redislocation in the tibia group (Frank et al., 2018). The study found no significant differences in clinical outcomes of patients treated by distal tibia allograft compared to those treated by Latarjet transfer. There is currently insufficient evidence to discuss recurrence rates after distal clavicle autografts.

5.3 Arthropathy

The development of early degenerative changes in patients with shoulder instability is a well-known, yet not fully understood phenomenon, with significant implications for a young and active patient population. The natural history of dislocation arthropathy is discussed in the first chapter, while this paragraph focuses on the incidence after bone grafting procedures.

5.3.1 Coracoid Transfer Procedures

Overall degenerative changes have been estimated to be around 20-25% (Domos et al., 2017)(Gupta et al., 2015)(Longo et al., 2014). Hovelius and colleagues reported 23% moderate and 11% severe arthritis according to the Samilson-Prieto classification, in 31 patients with a 33-35 year follow-up after Bristow type coracoid transplantation. The authors noted high satisfaction rates in their population, and compared the findings with the prevalence of moderate/severe arthritis in untreated and unstable shoulders, which amounted to 39% after 25 years (Gordins et al., 2015)(Hovelius et al., 2008). Older patients (>22 years old), patients presenting with a history of high-energy trauma and patients with a habit of alcohol abuse demonstrated a higher risk of arthropathy. Interestingly, a larger percentage of patients undergoing Bankart repair were observed to develop osteo-arthritis, yet the severity of degeneration was greater in the group treated by bone graft (Hovelius et al., 2001).

The general consensus is that the rates of arthropathy between soft-tissue procedures and bone graft procedures do not differ significantly (Domos et al., 2017). Overall satisfaction is high in both groups, despite the prevalence of degeneration. Importantly, the variability in the grading of shoulder degeneration is a significant weakness in the evaluation and interpretation of results. Lädermann and colleagues specifically investigated the risks of arthropathy in 117 patients after Latarjet with a follow-up of 16 years. The authors reported age over 40 years old, surgical delay and lateral graft overhang to be risk factors for early degeneration. Interestingly, hyperlaxity was observed to be a protective factor in this respect (Lädermann et al., 2013). This ties in with our historical understanding of post-capsulorraphy arthropathy, which was associated with the overtensioning of anterior structures. Similarly, technical errors, such as lateral overhang, intra-articular hardware and prominent anterior hardware are often linked to early degenerative changes (Allain et al., 1998)(Hovelius et al., 2012). Tauber et al. found that despite the successful stabilization of failed primary procedures, they could not stop the progression of degenerative changes. This led them to conclude that once the arthritis process had commenced, further surgical intervention could not realistically halt it (Tauber et al, 2004).

5.3.2 Free Bone Grafting Procedures

Systematic reviews tend to report higher rates of osteo-arthritic changes after Eden-Hybbinette types of iliac crest bone grafting, compared to coracoid transfer surgery. One recent comprehensive analysis reported a 63.2% prevalence in the ICBG group compared to 43.5% in the Bristow-Latarjet population (Papalia et al., 2018). As discussed earlier, the historical cohorts may have implanted iliac crest grafts as anterior bone blocks rather than as glenoid augmentations. Furthermore, the frequent use of iliac crest grafts as a salvage method for failed previous procedures may have led to the association of worse clinical and radiographic results with this type of surgery (Lunn et al., 2008)(Young et al., 1991). More recently, Rahme and colleagues reported 47% degenerative changes, with 30% moderate-severe, after a mean of 29 years using the Eden-Hybbinette procedure without fixation devices. This was a considerable decrease from the 58% moderate-severe arthritis reported by Hindmarsh and Linden using an Alvik-type modification. Auffarth and colleagues reporting on the long-term results of the J-Bone procedure found a 22% incidence of arthritis, on top of the 22% who presented with arthritis changes preoperatively. There were no reported cases of severe degeneration after a mean of 106 months (Auffarth et al., 2008). Similarly Warner et al., and Steffen and Hertel reported no or minimal evolution of degenerative changes in their respective studies (Warner et al. 2006)(Steffen and Hertel., 2013).

The role of capsular interposition in the prevention of arthritis in unclear. Supposedly, capsular interposition would avoid direct abrasion of the humeral head cartilage by the graft (Steffen and Hertel, 2013). However, there is little evidence to support this. Moreover, Auffarth and colleagues reported on the presence of a soft-tissue layer found on the surface of the intra-articularly positioned J-Bone grafts during postoperative imaging exams. Biopsies revealed this material to have “hyaline-like” histological qualities (Auffarth et al., 2018). As part of the same continuous effort to reduce arthritic postoperative changes, some surgeons have explored the use of fresh osteochondral grafts with matching articular properties. Most popular amongst these are the distal tibia allograft and the distal clavicle autograft. Both have shown great promise in biomechanical laboratory testing, yet clinical long-term trials are awaited before any statements can be made in regards to arthropathy rates (Bhatia et al., 2013)(Noonan et al.)(Willemot et al., 2018)(Kwapisz et al., 2018).

5.4 Graft Related

5.4.1 Position

Ideal graft position has been the topic of considerable debate. Not in the least because assessment of bone graft positioning on imaging is complex. Radiographic studies may provide some insight, yet are generally not considered sufficiently accurate. Dedicated CT-based measurements have been outlined by Kraus and colleagues (Kraus et al., 216). However, despite vastly improving the accuracy of graft placement evaluation, the methods are prone to errors relating to 3D object orientation, cartilage imaging and lack of universally accepted methodology. Regarding supero-inferior placement, biomechanical experiments performed by Nourissat have indicated that grafts were ideally positioned at the 4 o’clock position. Our own cadaveric work suggested placing the graft at or below the glenoid equator, depending on the supposed direction of translation (Nourissat et al., 2014)(Willemot et al., 2015). Clinically, there exists circumstantial evidence that grafts positioned too inferiorly may be associated with recurrent “over-the-top” anterosuperior instability or escape (Hovelius et al., 2012)(Willemot et al., 2019). Furthermore, biomechanical and clinical evidence have indicated that extreme inferior positioning may impede inferior screw purchase, and thereby, rotational graft stability (Weppe et al., 2011)(Gasbarro et al., 2016). Excessively superior grafts tend to occur more frequently, and may also theoretically result in recurrent instability, although there is little direct evidence of this in the literature. High grafts have been associated with suprascapular nerve injury by screw penetration (Gupta et al., 2015). Lädermann investigated the risk of suprascapular nerve injury as a result of screw orientation in cadaveric specimen and reported an increased risk with screws angled more than 10° posterior to the axial plane (Lädermann et al., 2012) Medially placed grafts have been associated with recurrence in several studies (Allain et al., 1998)(Lunn et al., 2009)(Metais et al., 2016). Hovelius and colleagues reported an 83% recurrence rate in patients with grafts positioned 1 cm medial to the glenoid rim (Hovelius et al., 2012).

Laterally overhanging grafts on the contrary, have been associated with early degenerative changes in clinical studies (Hovelius et al., 1983)(Allain et al., 1998)(Mizuno et al., 2014). These findings have been corroborated by evidence from pressure mapping studies showing increased peak forces generated by proud graft placement (Ghodadra et al., 2010). Overall, it is generally accepted to place the graft flush with the articular surface, or a few millimeters medial to it, below the level of the glenoid equator. With this position, the aim is to restore articular congruity and reconstruct the biomechanically important anatomical inferior glenoid circle. The aforementioned graft positioning coincides with the location of the glenoid defect in the most common vertical pattern of anterior glenoid bone loss (Huysmans et al., 2006)(Saito et al., 2005). Implant-free iliac crest graft techniques have supported these recommendations by demonstrating the remodeling of grafts to the supposed “native glenoid” after implantation (Anderl et al., 2016).

In regards to the accuracy of graft positioning, studies have indicated malpositioning in up to 67% of cases after open surgery (Allain et al., 1998)(Hovelius et al., 2012)(Mizuno et al., 2014). The new arthroscopically assisted techniques have reported increased positioning accuracy reaching 76% - 96% of grafts in Bristow-Latarjet procedures (Castricini et al., 2013)(Kany et al., 2015)(Cunningham et al., 2016)(Gendre et al., 2016). A comparative study into the positioning of J-Bone grafts in open and arthroscopic surgery revealed no significant differences except the higher placement of J-grafts in the arthroscopic group (Ernstbrunner et al., 2018). Arthroscopically assisted and all-arthroscopic procedures have the advantage of allowing careful assessment of the graft-articular surface interface. However, vertical graft placement may be more difficult to visualize than during open surgery. Whether bone grafts should be placed flush with the articular surface or with the subchondral bone is disputed (Ernstbrunner et al., 2018)(Dumont et al., 2014).

5.4.2 Graft Healing

Systematic reviews have estimated the prevalence of pseudarthrosis or non-union of coracoid grafts after Bristow-Latarjet between 1 - 9.1% of cases (Griesser et al., 2013)(Williams et al., 2018). Hovelius reported 13% non-union, with 5% migration of grafts in their long-term review (Hovelius et al., 2012). However, the routine incidence of asymptomatic non-union should not be confused with symptomatic graft loosening. The literature is scarce on this topic because large-scale CT follow-up of asymptomatic patients is ethically inappropriate. Samim and colleagues reported only 2 non-unions in a population of 41 patients 6 months after Bristow-Latarjet (Samim et al., 2018). Pseudarthrosis is typically related to improper surgical technique and biological factors. Single screw fixation and unicortical, instead of bicortical purchase have been linked to increased rates of non-union in clinical studies (Walch and Boileau, 2000)(Cassagnaud et al., 2003)(Mizuno et al., 2014)(Gasbarro et al., 2016)(Willemot et al., 2019). The matter of cortical fixation is expanded upon in the following paragraph on hardware-related complications. Apart from mechanical factors, smoking and old age are amongst the most prominent factors influencing bony healing in orthopedic surgery, and there is little reason to assume it to be any different in anterior glenoid bone grafting procedures. Inferior fusion rates and increased pseudarthrosis formation are well-documented in the general orthopedic literature (Schuind et al., 2017)(Hess et al., 2018)(Phan et al., 2018), and there is some direct evidence of the role of biological parameters in healing rates after shoulder instability (Gendre et al., 2016)(Boileau et al., 2016).

Contrary to popular belief, the coracoid transfer procedures should not be considered a “vascularized” procedure, and as such should not be associated with greater healing potential than free bone grafts. Hamel and colleagues meticulously verified the blood supply of the coracoid after dissection and osteotomy, revealing that all arterial blood supply routes were cut during the Latarjet procedure (Hamel et al., 2012). Surgical technique, nevertheless, is of great importance. It is advocated to thoroughly decorticate and flatten the mating bony surfaces in order to improve bony healing (Domos et al., 2017). Anatomical research has confirmed the increased available fusion surface area in traditional Latarjet compared to the Congruent-Arc modification (Dumont et al., 2018)(Montgomery et al., 2017). Moreover, the more precarious biomechanical fixation of congruent-arc constructs may increase the risk of pseudarthrosis (Giles et al., 2012)(Montgomery et al., 2017). There is however, no clinical evidence to support this theory. In regards to allograft fusion rates, a historical concern exists regarding graft resorption and healing (Stevenson et al., 1991)(Chapovsky et al., 2005). However, Provencher and colleagues reported 89% healing rates with distal tibia use. Interestingly, the authors remarked that a higher graft angle (>15°) increased the risk of non-union. The graft angle is an indirect reflection of the accuracy of bony apposition. Persistence of an excessive gap between the bony surfaces is more likely to induce fibrous healing (Provencher et al., 2016).

5.4.3 Resorption

Di Giacomo reported 59.5% graft resorption or osteolysis in a series of 26 patients after Latarjet procedure (Di Giacomo et al., 2011). The authors found the superior part of the graft to be more susceptible to osteolysis. Similarly, Zhu et al. reported a 90.5% incidence of resorption in their population at 1 year, although major/complete resorption occurred only in 49.2% (Zhu et al., 2015). Both Kordasiewicz and Haeni et al. reported similar rates of osteolysis in the superior part of the coracoid (Kordasiewicz et al., 2018)(Haeni et al., 2017). The etiology of graft resorption is not fully understood. However, recent work by Anderl and colleagues, demonstrating the remodelling of J-Bone grafts after implantation, suggests that osteolysis may not be a pathological destruction, but a physiological adaptation of the graft to its new environment (Anderl et al., 2016). As part of Wolff’s law of bone formation, mechanotransduction is believed to sustain the graft bone stock where necessary, whereas superfluous graft areas are dissolved (Frost et al., 2003). This theory would explain why Di Giacomo and colleagues found significantly higher rates of osteolysis in patients with lower (<15%) amounts of anterior bone loss (Di Giacomo et al., 2014). A recent CT study of Latarjet reconstructions supports the idea of grafts remodeling until the native glenoid is restored (Kee et al., 2018). Whether or not resorption affects overall outcome is disputed. The cause and extent of resorption are likely important variables in the possibility of further instability. For instance, in our study osteolysis was often pronounced in cases of symptomatic non-union (Willemot et al., 2019). However, other authors have not found any association between resorption and poor outcomes, with the notable exception of hardware related problems arising from the disappearance of the graft (Gupta et al., 2015)(Domos et al., 2018).

5.4.4 Fracture

Graft fracture is reported to occur in 0.9-1.5% of cases (Griesser et al., 2013)(Williams et al., 2018). Although there is relatively little hard evidence, most fractures are believed to originate from the peroperative handling of the graft (Gupta et al., 2015)(Domos et al., 2017). Excessive decortication, inaccurate drilling and overtightening of screws may cause fracturing of the graft. In case of fracture, salvage efforts to affix the fragments with anchors or smaller screws can be attempted. Others have described conversion of the procedure to a conjoint-tendon-only transfer in cases with minimal bone loss (Tennent et al., 2016). In case of unsalvageable graft fracture, conversion to a free bone graft may be the most appropriate course of action (Gupta et al., 2015)(Domos et al., 2017). However, due to the rarity of this complication, there are no guidelines on the topic.

5.5 Subscapularis Injury

In previous decades, injury to the subscapularis muscle and tendon as a result of stabilization surgery has been recognized as a significant risk factor for postoperative shoulder dysfunction. Gross subscapularis rupture is a rare event after coracoid transfer, occurring in less than 1% according to Griesser et al. (Griesser et al., 2013). However, subtle subscapularis insufficiency seems to be more prevalent. Scheibel et al. found 53.8% subscapularis dysfunction after L-tenotomy for open Bankart repair. The authors also reported fatty degeneration and atrophy in the superior part of the muscle (Scheibel et al., 2006). Similar studies have found reduced muscular thickness and poorer function after vertical transection or L-shaped tenotomies (Picard et al., 1998)(Maynou et al., 2005). The exact pathogenesis of muscular atrophy and fatty infiltration is not completely understood although generally believed to be a combination of local injury to the muscle tissue, devascularization and denervation (Paladini et al., 2012). Several studies have demonstrated a significant impact of subscapularis insufficiency on shoulder function after anterior glenoid bone grafting. Paladini and colleagues found a weakening effect of the L-tenotomy and advised using the horizontal subscapularis split instead (Paladini et al., 2012). A more recent investigation has confirmed the preservation of subscapularis function, trophicity and minimal fatty infiltration using this splitting approach (Caubère et al., 2017). However, the same study did demonstrate a significant deficit in endurance in internal rotation compared to the healthy side. There is little published data on the influence of arthroscopic surgery on subscapularis injury. Kordasiewicz and colleagues reported no significant difference in subscapularis quality on MRI when comparing open and arthroscopic surgery (Kordasiewicz et al., 2018). However, even arthroscopic Latarjet procedures require a subscapularis split technique. Free bone grafts, on the contrary, can be introduced via the rotator interval, causing minimal subscapularis injury (Verborgt et al., 2013)(Kraus et al., 2014).

5.6 Neurovascular Injury

Systematic reviews have reported a 0.7 - 1.5% incidence of nerve injury after coracoid transfer procedures (Butt et al., 2012)(Griesser et al., 2013)(Williams et al., 2018). Shah and colleagues reported 2 axillary, 2 musculocutaneous and 1 radial lesion in a series of 48 open Latarjet procedures. The axillary lesions persisted and eventually required neurolysis (Shah et al., 2012). In a larger study on 416 Latarjet procedures, Gartsman et al. found nerve injury to be the most common short term complication. The authors reported a 3.1% incidence of lesions consisting of 7 axillary, 4 musculocutaneous and 2 suprascapular injuries. All were treated expectantly, and only one required superior screw removal to alleviate suprascapular nerve irritation (Gartsman et al., 2017). In contrast to these retrospective studies evaluating patients electrodiagnostically only when clinically suspicious, Delaney and colleagues prospectively performed neuromonitoring during the Latarjet procedure in 40 patients. The authors found a 20.6% incidence of (axillary) nerve lesions. Findings were correlated with glenoid exposure, traction on the coracoid graft and surgical time (Delaney et al., 2014). A follow-up study implementing a dedicated nerve-sparing surgical protocol limiting intraoperative arm positioning, retractor placement and graft manipulation, showed a reduction in nerve stretch injuries. Although statistical difference could not be reached, the authors did demonstrate the importance of surgical technique in the prevention of nerve injuries (Woodmass et al., 2018).

The risk of suprascapular nerve injury by incorrect screw placement is a relevant concern. Divergence of more than 10° from the glenoid plane risks injuring the nerve, especially by the superior screw (Lädermann et al., 2011). There is some indication that arthroscopic Latarjet procedures have a higher risk of nerve injury, however, data is limited (Griesser et al., 2013)(Williams et al., 2018). Conversely, arthroscopic techniques using retrograde drilling may be putting the anterior neurovascular structures in peril. Reinares and colleagues found a significant risk to the axillary nerve when using retrograde K-wires (Reinares et al., 2018).

Several authors have demonstrated the altered position of neurovascular structures after Bristow-Latarjet procedure. The relative lengthening and angulation of the musculocutaneous nerve, by inferiorization and medialization of the coracoid process, may contribute to the rare cases of acute and delayed onset nerve palsy (Clavert et al., 2009). These non-anatomic changes and absence of safety landmarks make revision surgery after coracoid transfer exceptionally risky (Freehill et al., 2013). Nerve stretch injuries are typically treated conservatively. Dedicated CT images should be requested to rule out technical errors involving graft and screw placement. Electrodiagnostic studies should be obtained at 3 weeks and 3 months to monitor recovery. In the absence of spontaneous recovery, the patient should be referred to a specialist brachial plexus unit. Vascular injury is rare in coracoid transfer surgery. Griesser et al. found a 1.4% incidence across open and arthroscopic techniques (Griesser et al., 2013). The axillary artery is the most frequently injured vessel and appropriate treatment should be sought in consultation with a vascular surgeon (Gupta et al., 2015). There are currently no reported cases of nerve injury after iliac crest, distal clavicle or distal tibia osteochondral graft augmentation. Neurological injury at the iliac crest resulting from graft harvesting is discussed in the next paragraph.

5.7 Donor Site Morbidity

5.6.1 Coracoid Harvesting

There is some debate in the scientific community concerning the risks of producing anatomical alterations such as those accompanying coracoid transfer in young patients. The Bristow-Latarjet procedures involve a medialization and inferiorization of the coracoid tip and attached conjoint tendon. The relative lengthening of the strap muscles may play a role in neurological injury as discussed above (Clavert et al., 2009)(Gupta et al., 2015)(Freehill et al., 2013). Relaxation of the conjoint tendon and release of the pectoralis minor tendon may also influence scapular position, due to the role of these structures as protractors and downward rotators of the scapula (Cerciello et al., 2015). Moreover, the pectoralis minor muscle is not repaired to the coracoid stump in most Bristow-Latarjet techniques. Cerciello and colleagues investigated the incidence of scapular malposition after coracoid transfer. The authors reported a surprising initial increased protraction of the scapula, which they believed to be the result of pectoralis major contraction or the result of adduction and internal rotation of the humerus in resting position. However, at 6 months after surgery, the researchers found a restoration of symmetry between both shoulder blades on CT imaging (Cerciello et al., 2015). Critics of the study have pointed to the horizontal and static imaging modality of the shoulder as an inadequate method of investigation for scapular dyskinesia. Carbone and colleagues clinically compared the incidence of scapular dyskinesia in patients with coracoid transfer surgery compared to those treated by iliac crest augmentation. The authors found a significantly higher incidence of scapular malposition in the former group. However, the presence of dyskinesia was not associated with inferior clinical outcome scores in the study (Carbone et al., 2015). Similarly, sectioning of the CAL has been shown to reduce resistance to superior migration of the humeral head (Degen et al., 2013). However, there have been no clinical or radiographic studies to corroborate the resulting increased risk of impingement, cuff tear arthropathy or superior glenoid arthritis after coracoid transfer. Further research is required to establish the role of non-anatomic changes associated with coracoid transfer on the glenohumeral joint.

5.6.2 Free Bone Graft harvesting

Overall, free bone grafts are associated with a lower risk of neurovascular injury compared to Bristow-Latarjet transfers. However, iliac crest graft harvesting has been known to cause lateral cutaneous femoral nerve injury in 10% of cases. Most of these are transient, although some injuries may persist as pain or hypoesthesia. Surgical incision and size of the crest graft have been correlated to the risk of injury (Mirovsky et al., 2000). Moreover, structural graft harvesting can result in hematoma, fracture and pain at the iliac crest in up to 13% of cases (Almaiman et al., 2013)(Lädermann et al., 2018). Contrary to intuition, autologous distal clavicle harvest is not associated with significant morbidity to the shoulder. Distal clavicle resection is well tolerated in both older patients suffering from AC arthritis and athletes undergoing the procedure for distal clavicle osteolysis, providing that resection is kept under 1 cm (Charron et al., 2007). Excessive excision may cause injury to the coracoclavicular ligaments and result in subsequent AC instability (Tokish et al., 2014). Allogeneic osteochondral grafts are not associated with donor site morbidity, but are disadvantaged by lower availability, increased costs and risks of infectious contamination (Provencher et al., 2017).

5.8 Hardware

5.8.1 Screw Prominence

The most common complications following anterior glenoid bone grafting are related to fixation hardware. Griesser and colleagues reported that 35% of all reoperations after Bristow-Latarjet were aimed at removing symptomatic hardware. Intra-articularly positioned fixation devices inevitably lead to early degenerative changes and must be removed as soon as possible (Gupta et al., 2015). Prominent screw heads causing pain in external rotation are believed to be the result of inflammation of the subscapularis muscle and may be an indication for removal. Similarly, excessive screw length causing irritation to the posterior structures may be a reason for hardware removal (Metais et al., 2016). As mentioned above, suprascapular nerve injury has been correlated to screw position and length (Lädermann et al., 2011). Cadaveric studies have identified a safe zone for screw protrusion between the posterior glenoid rim and 2 cm medial to it. This has been equated to an angle of 10 - 28° in the transverse plane, and 29° in the sagittal plane (Bigliani et al., 1990)(Shishido et al., 2001). However, nerve position has been reported to vary according to scapular position (Longo et al., 2015). Alternatively, shorter screws can be employed to reduce the risk of posterior prominence. However, this tactic increases the risk of insufficient immediate fixation rigidity as detailed below. Hardy et al. reported inaccurate screw length in 65% of cases in a cadaveric study. The same authors have since demonstrated the utility of preoperative planning using CT images in the prevention of hardware length inaccuracy. (Hardy et al., 2018). Alternatively, novel fixation methods have been proposed in an effort to reduce the number of hardware-related complications. These techniques are discussed in the final chapter of this thesis.

5.8.2 Fixation Strength

5.8.1 Introduction

Various types and lengths of screws are used in anterior glenoid bone grafting. As mentioned above, insufficiently rigid fixation is believed to be associated with graft non-union, hardware loosening, screw breakage, bone destruction and recurrence of instability. We performed a biomechanical study on idealized sawbone models to investigate the role of currently used screw models and dimensions on construct stability.

5.8.2 Methods

Testing was performed on polyurethane foam block models to limit the experimental difficulties resulting from the use of human cadaveric bone such as inconstant anatomical dimensions, degenerative changes and variable bone quality. The generic 20 lb/ft3 rectangular foam blocks were fitted with a 2 mm thick short fiber filled epoxy resin laminate to replicate the material properties of cancellous bone with a cortical shell (Sawbones Inc. Vashon, WA, USA) (Mimar et al., 2008)(Lethinen et al., 2004)(Tingart et al., 2004). The resin layer was machined down to a thickness of 1.5 mm to match physiologic human glenoid cortex thickness (Mimar et al., 2008). Cancellous and cortical density were 20 and 102 pounds/square foot respectively. The rectangular block measured 21.7 x 39 x 40 mm, representing the average glenoid width and height after creation of a 25% defect (Fig. 5.7)(Iannotti et al., 1998). The anterior bone grafts were created from the same material. The composite graft dimensions, 13.7 x 9.3 x 26.4 mm were based on previously published measurements of harvested coracoid processes, since these are the most frequently used grafts. However, a simple quadrangular shape was chosen to allow extrapolation of results to other types of grafts such as tibial plafond allografts and iliac crest autografts (Young et al., 2013). Similarly to clinical conditions with significant glenoid bone loss, the model contained a flat anterior cancellous surface apposed to a flat cancellous graft surface (Burkhart et al., 2007).

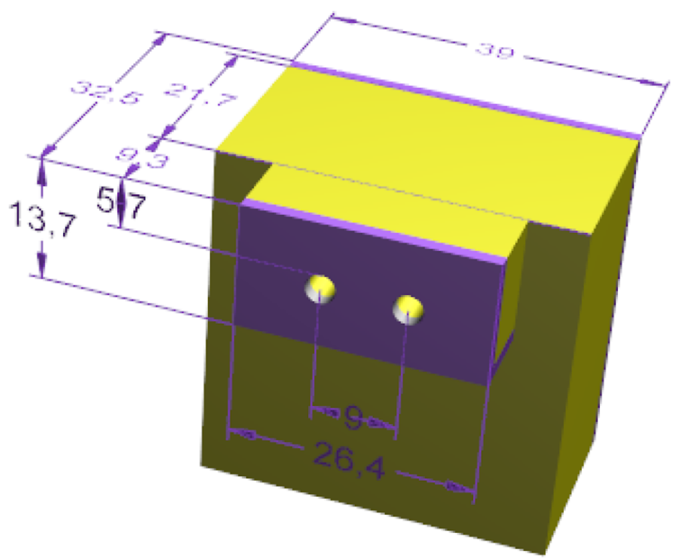

Figure 5.7
3D drawing of the stylized foam bone model consisting of coracoid with pilot drill holes and glenoid. Light color indicates cancellous bone, darker color indicates cortical bone. Measurements are shown in millimeters.

Three commonly used screws were selected for the experiment. The Arthrex 3.75 mm titanium cannulated screw (Arthrex, Naples, FL, USA), Mitek 3.5 mm titanium cannulated Bristow-Latarjet Instability Shoulder Screw (Depuy Synthes Mitek Sports Medicine

Raynham, MA, USA) (Fig. 5.8.) and the Synthes 4.5 mm steel Large Fragment LCP System Malleolar Screw (Synthes, West Chester, PA, USA) (Fig. 5.8). The Arthrex screws (major diameter 3.75 mm, shaft diameter 2.4 mm, thread pitch 1.8 mm), part of the Glenoid Bone Loss Instrument Set, are self-drilling, self-tapping screws. They are partially threaded, and a popular choice when performing a congruent-arc Latarjet procedure. The Mitek system (major diameter 3.5 mm, shaft diameter 3.0 mm, thread pitch 0.75 mm) includes titanium Top Hats, which are used as position holders and are inserted prior to screw insertion to prevent graft fracture. The partially threaded stainless steel Synthes screws (major diameter 4.5 mm, shaft diameter 2.9 mm, thread pitch 1.75 mm) are used for fracture fixation as part of the Synthes Large Fragment set. They are considered the “gold standard” in glenoid bone block fixation. Technical specifications are listed in table 5.2. (Table 5.2). Short and long screws lengths were selected for each screw type (Table 5.2). Combinations of short and/or long screws allowed for testing in 3 configurations: (1) both screws with unicortical purchase (unicortical-unicortical), (2) one unicortical and one bicortical screw (unicortical-bicortical) and (3) both screws with bicortical purchase (bicortical-bicortical). Six constructs of each screw type and length configuration were produced, amounting to a total of 54 models. Short screw lengths were selected from the manufacturer’s available range per type to minimize the variability of effective intraglenoidal length. Intra-osseous length was set at 30mm for all screws (table 5.2), replicating a realistic intra-operative scenario. Long screw lengths were chosen to guarantee bicortical purchase beyond the screws' spike tip. Two parallel pilot holes were drilled 9 mm apart, centered on the anterior cortical graft side according to the manufacturer’s instructions. Screws were inserted and tightened with a digital torque measuring screwdriver (Model STC50CN, Tonichi, Buffalo Grove, IL, USA). Average torque of “two-finger tightness” was determined from the authors' mean torque measurements.

Table 5.2

Manufacturer	Description	Size	Part number	Nominal length (mm)	Intra-osseous length (mm)	Thread pitch	Shaft length	Thread length	Shaft/thread length ratio
Arthrex	Screw, partially Threaded	3.75	AR-7000-32S	32	30	1.8	20	8	40%
			AR-7000-38S	38	Bicortical	1.8	24	10	42%
Mitek	Bristow – Latarjet instability shoulder screw	3.5	285121	32 (modified to 30)	30	0.75	10	20	200%
			285117	38	Bicortical	0.75	13	28	280%
Synthes	Malleolar screw	4.5	215.035	35	30	1.75	10	12	92%
			215.045	45	Bicortical	1.75	10	16	84%

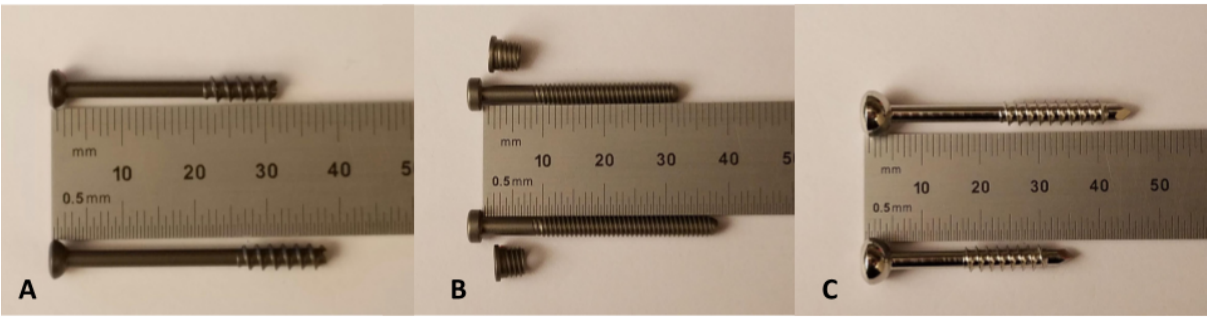

Figure 5.8
Photograph of the Arthrex 3.75 mm titanium cannulated screw (A), Mitek 3.5 mm titanium cannulated Bristow-Latarjet Instability Shoulder Screw (B), Synthes 4.5 mm steel Large Fragment LCP System Malleolar Screw (C).

After screw insertion, bone blocks were loaded into a vice and subjected to a cyclic loading staircase protocol based on previous work by Giles and colleagues (Giles et al., 2012). Testing apparatus consisted of an Instron Model 5944 (Instron, Norwood, MA, USA). The system was manually preloaded with 2N to 5N of force centered on the “articular” side of the graft removing all slack from the system (Fig. 5.9). The load and displacement of the grafts were then zeroed and the staircase protocol initiated. Loads were applied evenly with the help of a metal plate covering the lateral or “articular” surface of the graft. These simulated loads are an approximation of physiologic loading that may occur in the immediate postoperative period (Alvi et al., 2016). Additional loading of the graft by action of the conjoint tendon was omitted from our experiment for three reasons. First, this allows generalization of the results to all types of grafts, not exclusively the coracoid process grafts of the Latarjet-type procedures. Second, the direction and magnitude of conjoint tendon pull in the postoperative period has not been quantified accurately in the literature. Third, construct fixation strength is not believed to differ greatly between simulated loads in a pulling or pushing mode. Loading was repeated for 100 cycles at a frequency of 1 Hz. Load increments were 0-5N, 5-10N, 10-25N, 25-50N, 50-100N, 100-150N, and 150-200N. Graft displacement was measured continuously (Fig. 5.9). Failure was set at 0.8 mm of shear displacement, based on previously published fracture healing data (Schell et al., 2005)(Augat et al., 2006).

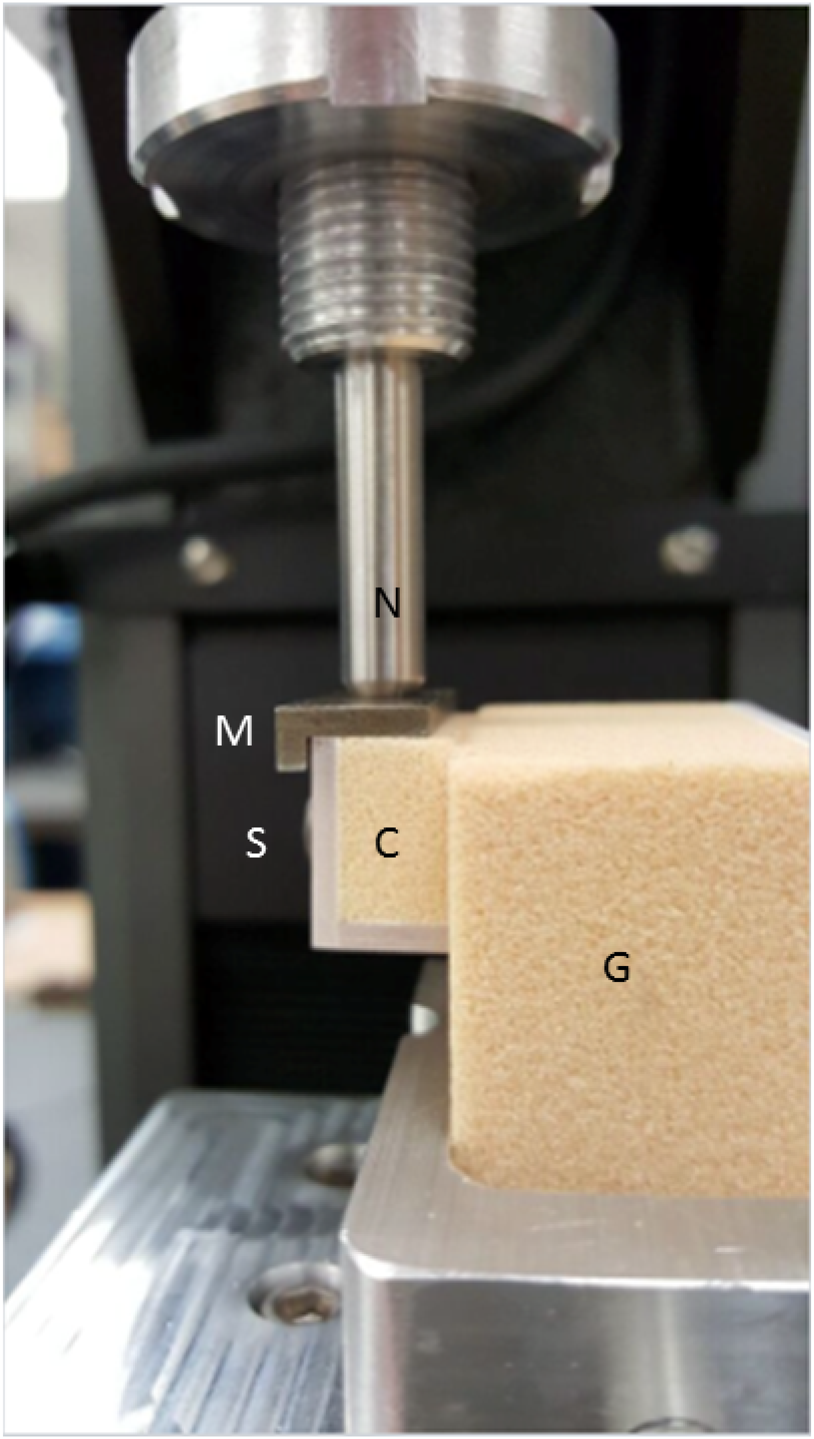

Figure 5.9
Photograph of mounted model during load application. G: Glenoid model, C: Coracoid model, S: screwhead, M: metal plate, N: loading nose.

Graft displacement was recorded as the final displacement during the last cycle of each loading increment. If a 0.8 mm displacement was achieved before maximum loading was completed, the cyclic loading was discontinued and the load and displacement at that point recorded. Statistical analyses of displacement data was performed by way of ANOVA test for each loading step. In the case of a significant result, further analysis composed by a series of T-tests was performed. Significance was defined as $P<0.05$. Power analyses were calculated with pilot data a priori, indicating that 6 models per condition would achieve a minimum power of $\beta=0.8$.

5.8.3 Results

Graft configuration with two bicortical screws demonstrated maximal displacements of 0.26, 0.26 and 0.25 mm (SD 0.01, 0.02 and 0.04 mm) at 200N loads for the cannulated Arthrex 3.75, the cannulated Mitek 3.5 and the solid Synthes 4.5 screws respectively (Fig. 5.8). ANOVA statistical analysis did not show a significant difference between the final displacements at any of the incremental loads. Graft fixation with a unicortical and a bicortical screw exhibited a significant difference in final displacements at 100N ($p=0.016$), 150N ($p=0.003$) and 200N ($p=0.002$). Maximal displacement at 200N reached 0.40, 0.25 and 0.24 mm (SD 0.12, 0.02 and 0.01 mm) for the respective screw types (Fig. 5.9). Similarly, graft fixation with two unicortical screws resulted in a significant difference of displacements at 100N ($p=0.005$), 150N ($p<0.001$) and 200N ($p<0.001$). Maximal observed graft displacements were 0.74, 0.27 and 0.24 mm (SD 0.04, 0.01 and 0.01 mm) for Arthrex, Mitek and Synthes screws respectively (Fig. 5.10). ANOVA per screw type revealed a significant statistical difference at 200N for the cannulated Arthrex screw 3.75 mm between the two unicortical and two bicortical, as well as between the two unicortical and unicortical-bicortical configurations. The observed displacements were 0.74 (SD 0.04) and 0.26 (SD 0.01 mm) ($p<0.001$) and 0.74 mm (SD 0.04 mm) and 0.40 mm (SD 0.13) ($p<0.001$). ANOVA comparison between the unicortical-bicortical and two bicortical configuration did not reach statistical significance. Similarly, comparisons for the cannulated Mitek 3.5 mm screws showed a trend towards greater displacements in the unicortical fixation compared to the unicortical-bicortical or bicortical fixation. However, these differences were not statistically significant. The solid Synthes 4.5 mm screws at the 200N loading demonstrated the smallest variation of all three screw types. There were there no statistically significant differences in graft displacement between the three configurations, nor were there any trends (Fig. 5.11).

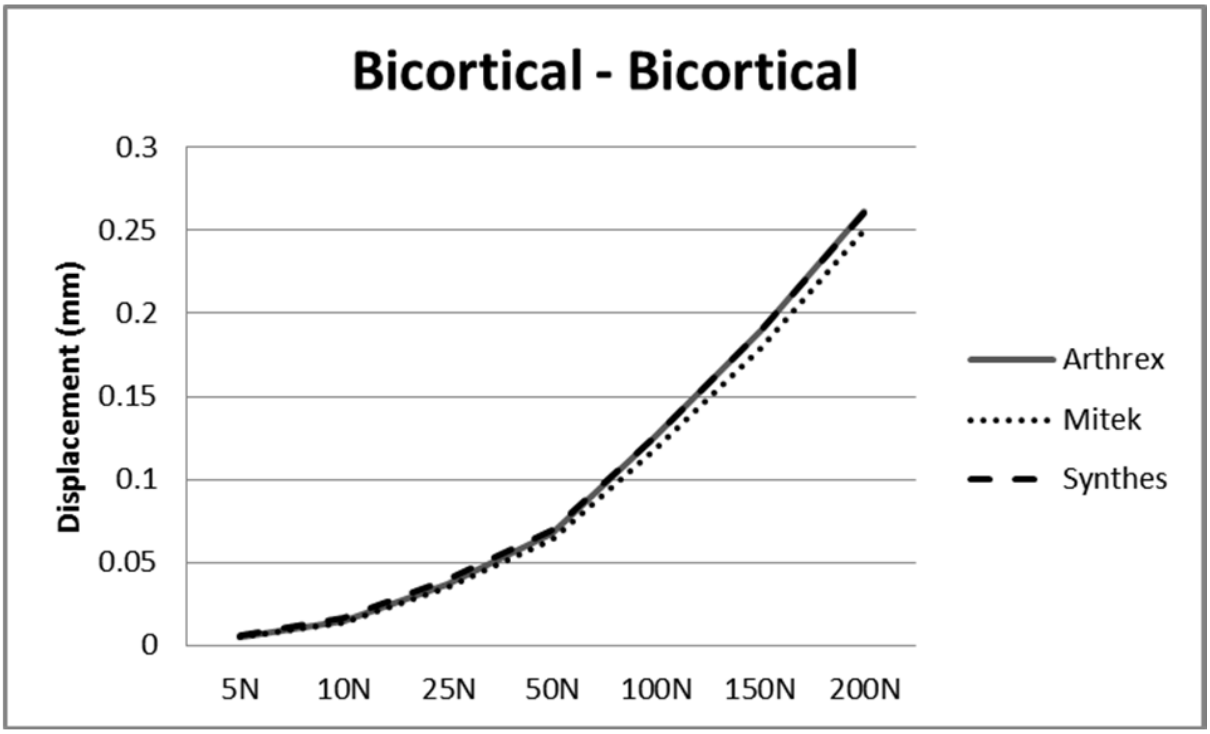

Figure 5.10
Line chart showing displacement (mm) vs. loading (N) for the bicortical-bicortical configuration. See figure legend for references.

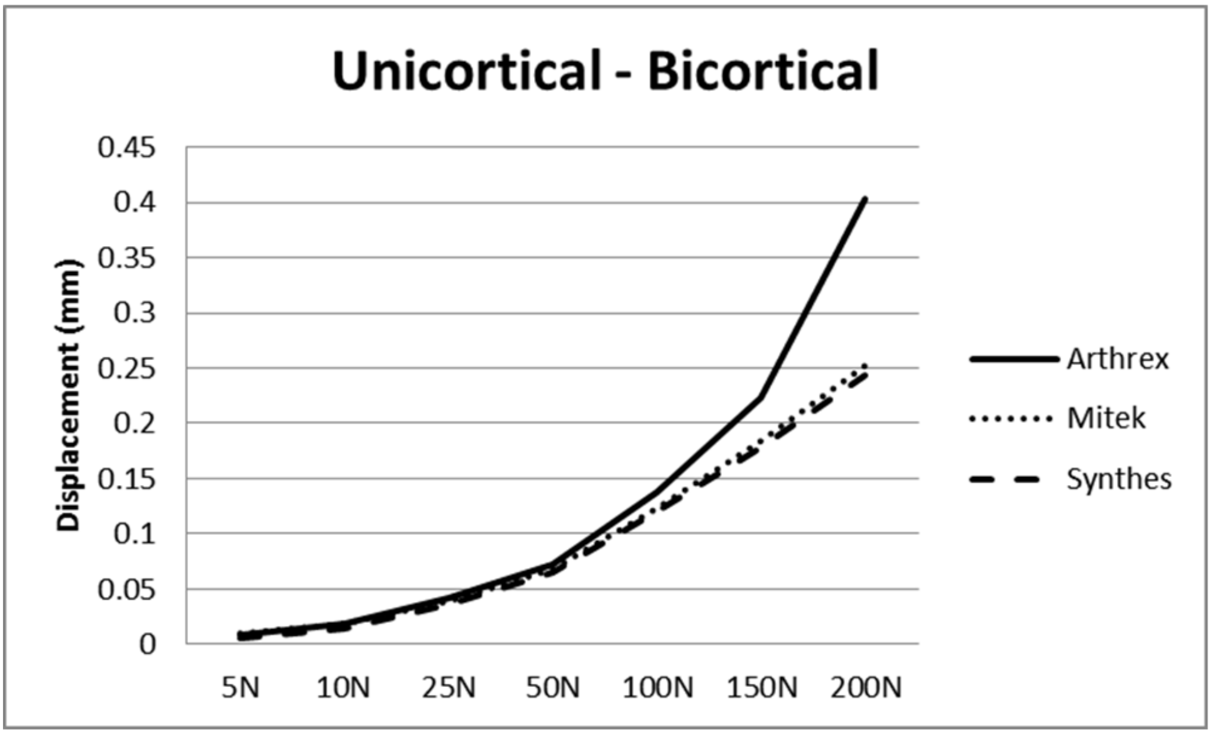

Figure 5.11
Line chart showing displacement (mm) vs. loading (N) for the bicortical-unicortical configuration. See figure legend for references.

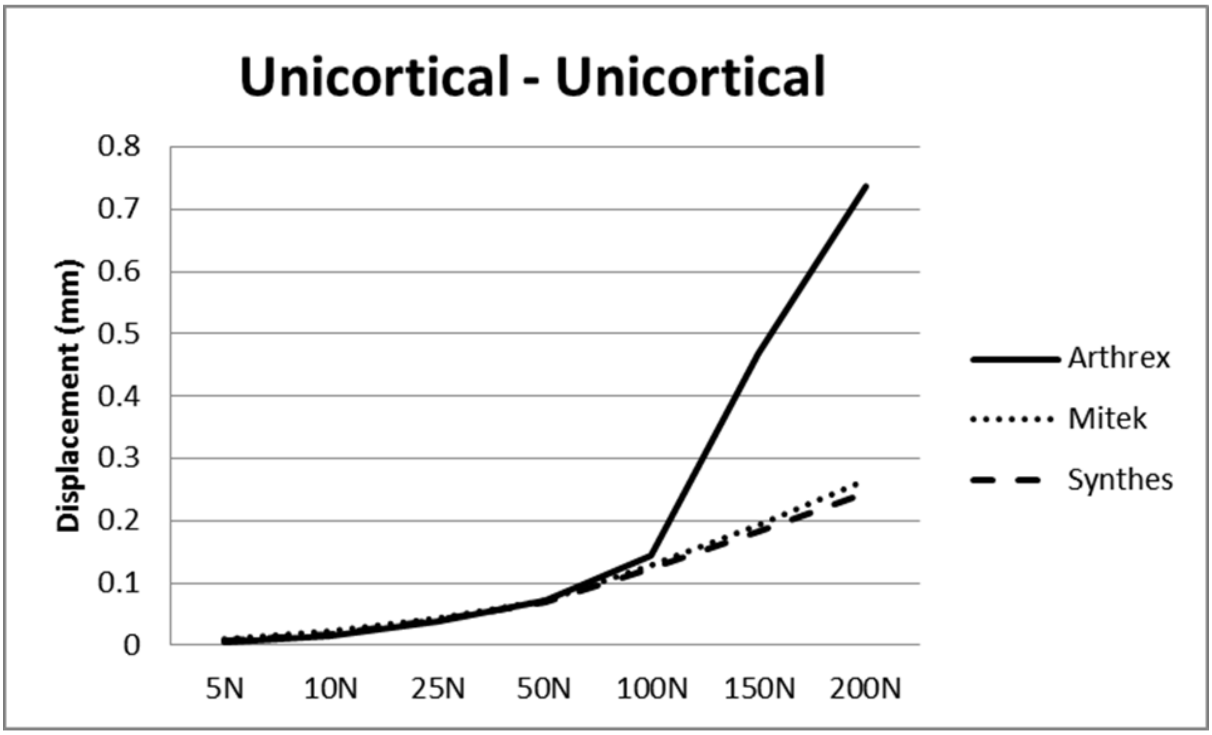

Figure 5.12
Line chart showing displacement (mm) vs. loading (N) for the unicortical-unicortical configuration. See figure legend for references.

5.8.4 Discussion

The Latarjet-Bristow and similar anterior glenoid bone grafting procedures are increasingly used in the treatment of patients with recurrent shoulder instability and glenoid bone deficiency (Beran et al., 2010). Although recurrence is infrequent or even absent in some series (Hovelius et al., 2012)(Mizuno et al., 2014)(Dumont et al., 2014), a relatively high complication and reoperation rate has been reported (Griesser et al., 2013)(Gupta et al., 2015)(Butt et al., 2012). Clinical studies have shown the importance of correct graft-to-bone healing (Lunn et al., 2008)(Young et al., 1991)(Boileau et al., 2010). However, construct strength and rigidity have to be weighed against hardware complications. As such, fixation technique remains an area of debate. This biomechanical study confirms that three screw types, commonly used in the setting of glenoid bone grafting, resist repetitive physiologic shear loads without clinically significant displacement when both screws attain bicortical purchase. Additionally, this study demonstrates that where the cannulated Mitek and solid Synthes screws performed satisfactorily in a unicortical-unicortical and unicortical-bicortical configuration, the cannulated Arthrex screws showed significantly larger shear displacement during the higher loads in those configurations. The Arthrex screws exhibited the smallest shaft diameter, the coarsest pitch, a larger thread rise and the lowest shaft/thread length ratio of the three screw types in this experiment (Table 5.2). The mechanism behind the inferior performance in unicortical configuration may be due to a combination of the smaller amount of cancellous "bone" in shear (coarse pitch and short thread length), the larger bending moment about the fulcrum point (low shaft/thread length ratio) and the passage of large threads creating bone voids (large thread rise) which may weaken the supportive bone stock.

Studies examining the biomechanical rigidity of fixation techniques for glenoid bone loss are sparse. Clinically, Shah and colleagues found a significantly higher rate of recurrence and non-unions in patients treated with cannulated screw fixation compared to the solid screws. The authors hypothesized the failures may have been linked to the reduced thread depth of cannulated screws (Shah et al., 2012). Weppe et al. compared the load to failure of a bicortical screw technique versus a bioabsorbable interference screw (Weppe et al., 2011). In 10 cadaver specimens, the median load to failure was 202 N and 110 N for the bicortical screws and the interference screw respectively. Alvi et al compared energy and cycles to failure between 3.5 mm stainless steel cortical screws and 4.0 mm stainless steel partially threaded cannulated cancellous screws (Alvi et al., 2016). The authors found no statistically significant differences in either parameter. Shin et al., compared 5 groups of cancellous and cortical screws in both solid and cannulated form, in bicortical and monocortical fixation methods in fresh frozen cadavers. The experiment applied mediolateral force in a cyclical and failure test. However, the authors could not report any significant differences between the various screws and constructs (Shin et al., 2017). Conversely, Schmiddem and colleagues reported a 45% reduction in fixation strength between bicortical and monocortical fixation using a sawbones experimental setup. The authors used solid partially threaded cortical 3.5 mm screws in a anteroposterior pull-out, rather than a mediolateral loading, testing set-up (Schmiddem et al., 2018).

Load to catastrophic failure is an important parameter, however in our study subclinical displacement was chosen as the primary outcome parameter. The experimental set-up aimed to recreate the immediate postoperative environment before bony healing occurs. It was not the intention of the authors to simulate in-vivo loading of anterior glenoid bone grafts in this experiment, merely to assess immediate postoperative construct stability. Although, active motion is typically deliberately minimized during this postoperative period, it is believed that early micromotion plays a role in the development of pseudarthrosis. The threshold for clinically significant displacement of the graft was based on previous literature on fracture healing as adopted by Giles et al. (Giles et al., 2012). Non-union of a coracoid or other bone block following an anterior glenoid augmentation procedure is a recognized and clinically significant complication. Non-union may result in recurrent instability and the need for revision surgery. Griesser et al evaluated performed a systematic review, analyzing 45 studies (1904 shoulders). They reported a non-union rate of 9.1% (Griesser et al., 2013). Mizuno et al. reported an incidence of 1.5% in a series of 68 patients and Lafosse reported an incidence of 1.7% in a series of 62 patients (Mizuno et al., 2014)(Dumont et al., 2014). It has, however, been established that standard radiographic techniques are not suited to evaluate bony healing accurately (Kraus et al., 2016).

Graft position may play a role in the development of graft pseudarthrosis. Grafts placed inferiorly on the glenoid can lead to poor inferior screw purchase and decreased rotational stability, resulting in a weak biomechanical construct (Weppe et al., 2011). Grafts placed too cranially can lead to recurrent instability (Hovelius et al., 2012) or suprascapular nerve injury (Shishido et al., 2001)(Lädermann et al., 2012). Grafts placed too medial or lateral can result in recurrence or secondary osteoarthritis, respectively (Hovelius et al., 2012)(Young et al., 1998). Willemot et al. recently described ideal graft positioning in the sagittal plane depending on the direction of dislocation (Willemot et al., 2015).

Furthermore, graft positioning may vary with technique modification. Giles et al. demonstrated a decrease in failure strength from 557N to 392N with forces applied in a mediolateral direction, between classic and congruent-arc Latarjet techniques in a cadaveric experiment (Giles et al., 2012). Similarly, Montgomery and colleagues recorded significantly lower failure loads and load-to-first-motion in female cadaveric specimen after congruent-arc Latarjet (Montgomery et al., 2017). However, due to the insecurity regarding the exact physiological loads in the postoperative phase, the consequences of these laboratory findings are uncertain. Proponents of arthroscopic anterior glenoid grafting procedures have cited more accurate graft placement under direct visualization as a possible advantage over open procedures. (Verborgt et al., 2013). While most technique guides stress the placement of both superior and inferior screws in a bicortical fashion to maximize fixation strength, it is the authors' experience that evaluation of bicortical position without the use of a postoperative CT scan can be difficult. Some surgeons will, to avoid complications associated with excessive posterior screw protrusion, accept one or two unicortical screws. The results of this study suggest that some commonly used solid and cannulated screws allow for one or even both screws to be placed in a unicortical manner without compromising the construct rigidity.

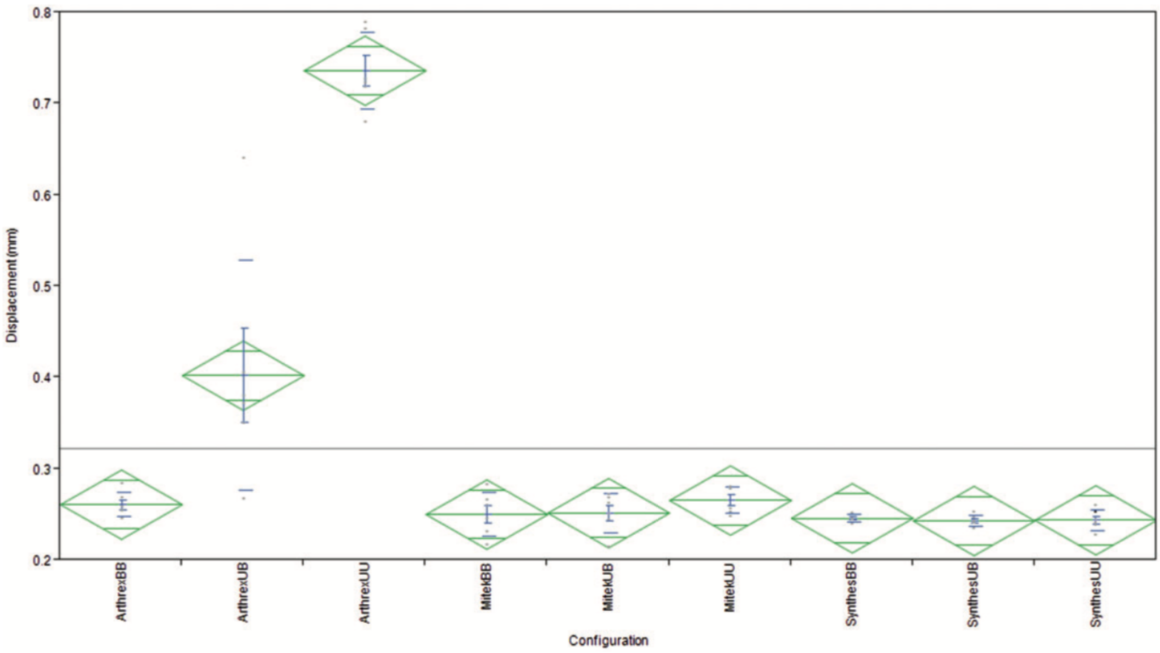

Figure 5.13
Diamond plot showing maximal displacement (mm) per configuration per screw-type. Green diamonds indicate confidence interval. Blue error bar indicates mean error. Blue lines indicate standard deviation. BB, bicortical–bicortical; UB, unicortical–bicortical; UU, unicortical–unicortical.

5.8.5 Limitations

Limitations of the present study were those inherent to a biomechanical study using clinical parameters in a nonclinical testing environment. The decision to use Sawbones (Sawbone Inc. Vashon, WA, USA) was made to increase the reproducibility and uniformity of the experiment. Most biomechanical studies related to graft fixation are performed on cadavers yet the variability of cadaveric bone has been shown to be highly unpredictable. Mechanical properties of cadaver bone have up to 19 times the inter-specimen variability compared to uniform bone models (Little et al., 2012). An abstract rectangular representation of the glenoid and graft was chosen instead of an exact anatomic model. This allowed for the elimination of anatomic and mechanical variability as a confounding factor. Moreover, in the case of large glenoid defects, a relatively flat cancellous anterior glenoid surface is mated with a prepared flat cancellous graft surface, which is why it was felt that an abstract flat shape would not diminish the applicability of the results. However, the use of non-anatomic geometry remains a limitation of the study. The conjoint tendon, capsular structures and rotator cuff action may influence graft loading postoperatively, human factors that may affect micromotion at time zero such as soft tissue and conjoint tendon traction were not simulated in this experimental set-up. Furthermore, although the cyclic loading protocol is a peer-reviewed standard for testing graft fixation strength, this experiment did not aim to simulate the actual physiologic loading environment after anterior glenoid bone grafting. The intention of the test was to assess different graft fixation modalities under carefully controlled laboratory settings.

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Chapter 6: Conclusions

“A learning experience is one of those things that says, 'You know that thing you just did? Don't do that.”

Douglas Adams, The Salmon of Doubt

Overview

The final chapter summarizes the findings of this thesis and its impact on daily clinical practice and discusses our preferred algorithms in the treatment of shoulder instability. The chapter also explores the latest developments in surgical treatment, as well as the direction of ongoing research in the field of glenohumeral instability and bone grafting.

6.1 Insights and takeaways

6.1.1 Introduction

The general aim of this doctoral work was to investigate the possibility of improving on the results of bone block procedures. The thesis specifically intended to investigate the potential of free bone grafts in providing a valid alternative to the classic coracoid transfer procedures in regards to stability while reducing the risk of peroperative and postoperative complications. In order to achieve this we divided the work in a sequence of research questions. Listed below:

What is bone block surgery? (**1**)
What are the biomechanical principles behind bone grafting procedures? (**2**)
Is free iliac bone grafting of an intact glenoid biomechanically sound? (**3**)
Is translational joint stiffness predictable, based on joint surface characteristics? (**4**)
What are the different graft options in cases of bony instability? (**5**)
What is the morphological profile of various graft types? (**6**)
What is the incidence and nature of failures after bone block procedures (**7**)
What is the biomechanical role of hardware in the graft fixation? (**8**)

Some valuable insights were gained during the execution and interpretation of the experiments performed for this doctoral thesis. In a general sense, this work has been one long exercise in conducting and understanding orthopedic biomechanical research. The experiences gained will undoubtedly influence the quality of future scientific endeavours as well as the critical appraisal of new publications. Furthermore, this thesis has provided a unique opportunity for hands-on cadaveric biomechanical testing, which has been of great value in the practical appreciation of anatomical variation, the direct experience of the material properties of human tissues and the role of implant design. Moreover, the writing of this doctoral thesis has been instructive in the fine-tuning of communicative, collaborative, problem-solving and time-management skills.

6.1.2 Research Aims

We reviewed the definition and meaning of “bone block surgery” in Chapter 2. We described the origins and development of both the coracoid based techniques, and the iliac crest based methods. We discussed the historical indications and hypothetical mechanisms behind bone grafting surgery in shoulder instability. Special attention was given to the many modifications within these bone grafting procedures, differentiating the classic Latarjet with two screws, from the screwless or singular screw Bristow techniques. We also reviewed the variations in graft position such as the on-end, lying-down and the Congruent Arc modification. We described, in-depth, the various iliac crest bone grafting procedures from Alvik type procedures to tricortical iliac crest grafting. We reviewed the literature on this topic, concluding that good results could be obtained when the graft is used in a revision setting after failed anterior bone grafting. The historically disappointing long-term results and high rates of osteoarthritis is explained by variations in grafting technique rationale and postoperative classification of degenerative changes, potentially regarding “normal” post-instability arthropathy as being caused by the grafting procedure. This literature review generated a vast amount of information on past and current usage of bone grafts in anterior shoulder stabilization. The open tricortical bone grafting procedure outlined in our 2015 technical paper highlighted the current standard of care in revision bone grafting, exposing certain weaknesses in the diagnosis and treatment of patients in need of bony stabilization, and laid bare clear gaps in our knowledge and understanding of both primary and revision bony shoulder instability (Willemot et al., 2015). The first chapter amply defined the nature and role of various bone grafting procedures within the treatment of anterior shoulder instability. This wide and explorative first research question did not have an immediate impact on our daily clinical practice, yet greatly improved our understanding of the niche field of bone block procedures, setting the scene for further research.

In Chapter 3 we further explored the biomechanical underpinnings of the aforementioned bone block procedures in order to answer our second research question. We reviewed the available literature on the biomechanics of shoulder instability, and more specifically, the role of anterior glenoid bone grafting. This review familiarized us with the various cadaveric and abstract methods used in the evaluation of shoulder instability. A deeper understanding and grasp of the biomechanical principles governing both the endrange and midrange of motion was gained from this exercise. We also came to the conclusion that in a head-to-head biomechanical comparison, free bone grafts tended to underperform compared to coracoid transfers. This had a direct impact on our daily clinical practice, explaining why Bristow-Latarjet remained our preferred stabilizing procedure in case of significant anterior glenoid bone loss. However, this led us to the next research question; does it make sense to use free bone grafts in glenoids with minimal or no bone loss? This question arose from the clinical observation that free bone grafts, who cannot boast the dynamic stabilizing effect of the conjoint sling of the coracoid transfer procedures, still seemed to successfully stabilize patients after failed Bristow-Latarjet. This observation combined with the attractiveness of free bone grafting procedures in regards to the choice of available graft types, the ease of graft harvesting, the limited or absent donor morbidity, the customizability of graft shape and size, the possibility of simple all-arthroscopic techniques, graft passage through the rotator interval without disturbing the subscapularis muscle, and overall anatomic nature and minimal invasiveness of the procedure (Verborgt et al., 2015), led to our curiosity towards the potential of free bone grafts as primary stabilizing procedures for anterior glenohumeral instability.

However, since several biomechanical papers had already proven the superiority of coracoid based techniques in glenoids with significant anterior defects, we hypothesized a role for free bone grafts in the subgroup of patients with a high risk profile, yet no bony glenoid defect. This included young active patients with hyperlaxity involved in contact sports for instance. The hypothesis led to the development of our cadaveric experiment testing the influence on bony stability of an iliac bone graft in the absence of glenoid bone loss. The results indicated a significant improvement in translational peak force required in the case of bone-grafted glenoids. We further deduced that the debate on graft positioning in the superior-inferior direction was not ideally answered by our experimental set-up, since translational force was heavily dependent on direction of dislocation. These initial findings were poised to change our daily clinical practice and surgical technique, yet results from simultaneous research into the complications of anterior bone grafting performed by ourselves and by non-associated researchers had, by then, revealed the risks of resorption and graft failure in cases of glenoid augmentation beyond the native glenoid size and shape. We therefore never initiated any clinical trials into the efficacy of anterior glenoid bone grafting in the absence of glenoid bone loss.

Conversely, analysis of the results of this basic stability cadaveric test, revealed a clear relationship between glenoidal shape and translational resistance after bone grafting. This led us to suppose that translational stiffness could be predicted by mere analysis of the reconstructed or augmented glenoid articular surface. Such a predictive formula, we believed, would be of great value in the elimination of superfluous cadaver tests, and would be extremely useful in the creation of a finite element glenohumeral stability model. It was the laboratory’s aspiration to create such a model as an adjunct to in-vitro tests, to increase the variabilities and conditions, without compromising valuable cadaveric specimen. We therefore decided to write a short technical note proving the feasibility of stability prediction purely based on surface geometry. The formulas were able to predict the behaviour of our randomly selected geometric shapes, under certain simplifying constraints such as sphericity and non-deformability. These findings and ideas directly influenced our clinical practice in regards to graft selection and graft positioning. From then on, more attention was paid in the correct positioning of the graft so as to not form a “bumper” or “block” to translation, but to restore the anterior glenoid rim to the native condition as closely as possible.

In a further quest to improve anterior glenoid reconstruction, we investigated the option of using alternative graft sources such as variations of coracoid positioning, iliac crest, distal clavicle, distal tibia allograft, and glenoid allograft, as detailed in Chapter 4. We performed an inventorizing review of the graft sources in the available literature, listing the various advantages and disadvantages of each. Coracoid transfer techniques boast the overwhelming biomechanical superiority, yet are associated with a high rate of donor site morbidity and complications. Iliac crest based techniques carry the burden of the historically associated high rates of arthropathy. Conversely, iliac crest grafts are customizable and relatively easy to harvest. Osteochondral grafts have the immense advantage of having an cartilaginous surface, whether under the guise of a distal clavicle fragment with the risk of local donor site issues, or as distal tibia or glenoid allografts. The latter option does encompass a higher cost, questionable cartilage viability, risk of communicable disease and availability issues. From this literature review it also became clear that much remained unknown about the shape of the articular surfaces of the grafts used for reconstruction. We therefore decided to perform a dedicated cadaveric study investigating the surface characteristics of the multiple graft options.

This next study, focussed exclusively on analysis of graft shape, revealed that classically positioned coracoid grafts were unpredictable, whereas congruent arc grafts were excessively curved compared to the glenoid surface. Bicortical iliac crest grafts were much better suited for reconstruction than tricortical grafts, and that distal tibia allografts did hold promise for glenoid reconstruction, especially in regards to coronal curvature. Glenoid allografts outperformed all other grafts, although these results were mainly used as a control group due to the scarcity of glenoid allografts in bone banks. This study clearly demonstrated that in contrary to our then-held beliefs, tricortical iliac crest grafts did not provide a congruent restoration of anterior glenoid rim, which deterred us from implementing an arthroscopic tricortical iliac crest bone graft augmentation in primary cases. The results provided a basis to further pursue the possibility of minimally invasive anterior rim reconstruction using a small arthroscopic bicortical iliac bone or osteochondral graft.

In Chapter 5 we tried reverse engineering the problem of coracoid transfer procedures. First of all, we performed a thorough literature review of failures and complications after anterior glenoid bone grafting. This review quickly revealed a higher burden of disease in the postoperative population than anticipated. The most common causes of failure and reasons for revision, were related to hardware. We therefore performed a retrospective analysis of failures at our institutions which helped to reconstruct the exact failure mechanism. Graft non-union, resorption, fracture and malpositioning were the main reasons for revision in our study. These findings convinced us of the inherent risks of symptomatic non-union after anterior bone grafting and had a direct impact on our clinical practice, disputing the contemporary held belief that graft non-union was innocuous. Symptomatic patients after bone grafting are much sooner evaluated by CT scan now, to assess these complications. The combined literature review and retrospective analysis also spurred us on to investigate the main culprit of Bristow-Latarjet failures, namely hardware. A dry lab biomechanical test was devised to compare three commonly used screw types for bone graft fixation. The testing protocol revealed the underperformance of the screw type with the largest difference in thread-to-shaft diameter and the lowest thread/shaft ratio in unicortical bone fixation.

These findings directly impacted our choice of hardware for this procedure. We furthermore hope to use the results of this study as a benchmark for further experiments with novel fixation techniques and devices.

In this doctoral thesis we explored some biomechanical and morphological facets of anterior glenoid bone grafting, as well as conducting a failure analysis and biomechanical investigation of hardware fixation. In all confidence we can state that free bone blocks are a valid, and in some cases preferred, alternative to traditional coracoid based anterior grafting techniques". However, further scientific exploration is required to evaluate the biomechanical and clinical behaviour of free bone block grafting in recurrent shoulder instability.

6.2 Treatment Algorithm

6.2.1 Introduction

The treatment strategy for traumatic anterior glenohumeral instability is complex. Due to our increasing understanding of the role of soft-tissue injuries, bone loss and patient characteristics, current surgical algorithms are constantly evolving. In the following paragraph we will present our treatment protocol for traumatic anterior shoulder instability in young and active patients exhibiting anterior glenoid bone loss based on the available evidence at the time of writing.

6.2.2 Preoperative decision making

The main factors influencing decision-making in cases of glenohumeral instability with anterior glenoid bone loss are the size and type of the lesions and the patient's demands. Adequate clinical and diagnostic exams should be performed to evaluate the first, and a thorough conversation should be had with the patient to assess the latter. Special attention is given to the presence of pain, apprehension, weakness, loss of range of motion, neurovascular abnormalities and hyperlaxity. Radiography is still recommended as a basic screening tool, yet is universally acknowledged to be inferior to advanced imaging techniques such as CT and MRI (Walter et al., 2019). Advanced imaging is usually indicated in recurrent instability, or in primary instability with a clinical or radiographic suspicion of concomitant injury. The type of imaging technique seems to be less relevant than previously thought, especially in regards to the appreciation of bone lesions. Both 2D and 3D multiaxial CT and MRI techniques have been shown to be reliable in the measurement of glenoid bone loss. And within these, best fit circle methods have proven their accuracy, and inter- and intraoberserver reliability, whether applied ipsilaterally or compared to the uninjured shoulder (Walter et al., 2019). In the preoperative decision-making, the degree of glenoid and humeral bone loss are of crucial importance. Therefore, a systematic measurement methodology and imaging modality should be agreed upon with the radiology department to insure consistency. Ideally, a percentage of inferior circle bone loss should be reported, or when such tools are not available, maximal glenoid width ratios. Humeral lesions are best described and evaluated according to the glenoid track concept as "on-track" or "off-track" as discussed earlier. These factors, in combination with the visualization of concomitant soft-tissue injuries are of great importance to the treating surgeon.

6.2.3 Treatment

Conservative treatment should always be considered. A brief period of immobilization followed by physiotherapy focussing on muscular balancing and range of motion may be sufficient for most low-demand and elderly patients. However, the literature is conclusive regarding the risk of recurrence in high-demand and, especially, young patients (te Slaa et al., 2004)(Hovelius et al., 2008)(Hovelius et al., 2016)(Balg and Boileau, 2007). Young and active patients will therefore much sooner be referred for surgical stabilization. In the absence of significant bone loss, most patients are treated with arthroscopic anterior labral repair and capsulorrhaphy as indicated, unless a specific humeral-sided soft-tissue lesion is suspected. The Instability Severity Index Score (ISIS) is a useful tool, based on patients age, physical activity, hyperlaxity and glenohumeral bone loss, to aid in decision-making regarding the choice between soft-tissue repair and anterior glenoid bone grafting (Balg and Boileau 2007). The authors also found glenoid and humeral bone loss to be the most influential factors in the risk analysis.

In the presence of a displaced fresh large bony Bankart fragment, surgical stabilization is indicated. This can be performed open or arthroscopically using hardware or suture anchors depending on the size of the bony fragment and the availability of tools and skills (Sugaya et al., 2005). Patients presenting with glenoid bone loss are preferentially stratified according to the glenoid track concept. Based on this theory, shoulders with an on-track Hill-Sachs lesion and glenoid bone loss under 25% should be sufficiently stable with a soft-tissue only repair. However, as detailed below, high-demand patients presenting with bone loss as low as 13.5% may also benefit from bony augmentation (Shaha et al., 2015). On-track lesions with more than 25% glenoid bone loss require bone stabilization in the form of anterior glenoid bone grafting. In cases with an off-track Hill-Sachs lesion but less than 25% glenoid bone loss a remplissage procedure may be preferred over anterior glenoid bone grafting in lower demand patients. Conversely, off-track lesions with less than 25% glenoid bone loss in high demand patients should be considered an indication for anterior glenoid bone grafting with or without remplissage. In off-track lesions with more than 25% bone loss, in which a classic Latarjet procedure is insufficient to convert the lesion to an on-track Hill-Sachs, additional remplissage of humeral head bony procedures can be attempted. Alternatively, a congruent-arc Latarjet or larger free bone graft can be selected for such cases (Itoi, 2017).

The glenoid track concept has recently been validated in the clinical setting. First, glenohumeral engagement was accurately predicted based on preoperative measurements of glenoid and humeral lesions, and secondly, implementation of the concept has demonstrated the ability to predict failures in Bankart repairs based on the on-track and off-track principle (Metzger et al., 2013)(Shaha et al., 2016)(Mook et al., 2016). However, we do sometimes opt to perform a coracoid transfer in the absence of significant glenoid or humeral bone loss for extremely high demand patients, or seasonal athletes who cannot afford to recur. The literature supports this more aggressive stance, citing better clinical outcomes with anterior bone grafting in patients with subcritical glenoid bone loss (>13.5%)(Shaha et al., 2015). In doing so, we may be overshooting the bony stability requirements of some patients, and more nuanced hybrid techniques may be better suited as discussed in the next paragraph. At our institution, the preferred method of anterior bone grafting in primary cases is still the open coracoid process transfer as described by Walch (Mizuno et al., 2014). Our research findings did suggest a role for free bone grafting in primary cases, however due to the low incidence of complications in our population, a switch to a novel free bone grafting procedure has not yet gone into effect. Similarly, we have not found any advantage to performing the procedure arthroscopically. The literature has indicated similar recurrence, revision and complication rates for both techniques. However, less postoperative pain, increased surgical time and persistent apprehension were associated with arthroscopic Bristow-Latarjet in two recent meta-analyses (Hurley et al., 2018). In major revision cases, we tend to adopt an open Eden-Hybbinette type tricortical iliac crest graft technique as described by Matsen (Rockwood and Matsen, 2009). This technique has shown good clinical outcomes in multiple studies (Lunn et al., 2008)(Warner et al., 2006). We have included a figure of our treatment algorithm below (Fig. 6.1).

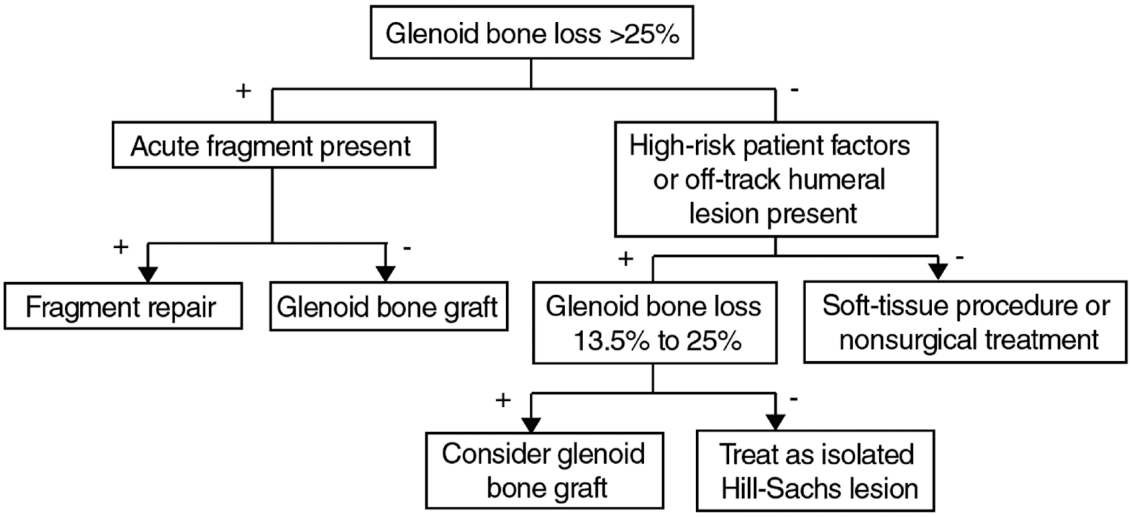

Figure 6.1
Treatment algorithm for shoulder instability presenting with anterior glenoid bone loss.

6.2.4 Evolving strategy

Arthroscopic shoulder surgery has slowly but steadily replaced the majority of soft-tissue-related open shoulder procedures in the last decades. Improved diagnostics, minimal invasiveness, reduced postoperative pain, lower infection rates and better cosmesis are the main drivers behind this evolution (Buess et al., 2005)(Baker et al., 2017). However, in field of bone block surgery, open procedures still have the upper hand. This is, in part, due to the complex nature of the arthroscopic Bristow-Latarjet procedure. Although, such techniques have been proven to work, the intense learning curve, long surgical time and possibility of catastrophic complications have deterred many shoulder surgeons (Castricini et al, 2013)(Cunningham et al., 2016). Few are willing to abandon the tried and trusted open coracoid process transfer in favour of the complicated arthroscopic equivalent. The open

Bristow-Latarjet procedure remains the gold standard in the treatment of traumatic anterior shoulder instability with glenoid bone loss. However, concerns relating to the non-anatomic nature of the procedure have spurred on the development of alternative, preferably arthroscopic, non-coracoid, anterior glenoid bone grafting techniques. Recent studies have highlighted the importance of bipolar lesions, and treatment strategies should evolve to deal with these combined gleno-humeral bone lesions (Gowd et al., 2018). However, coracoid transfers in patients with subcritical glenoid bone loss are related to a higher incidence of graft osteolysis and hardware complications (Di Giacomo et al., 2011).

We hypothesized that such patients might be treated with a soft-tissue procedure augmented by a small arthroscopic anterior bone graft (Willemot et al., 2015). Moroder and colleagues recently published a similar technique which they dubbed “Bankart plus” for the same indication. The authors report satisfactory clinical outcomes, yet long-term results are not yet available (Moroder et al., 2018). ALternatively, the J-bone graft technique is another method to create an anterior glenoid bony augmentation in an all-arthroscopic fashion using autologous bone. The J-bone method has shown excellent results after two years, but long-term follow-up data is not yet available (Anderl et al., 2016). A recent comparative clinical study evaluated the difference between arthroscopic and open J-bone procedures. The authors reported similar results and acceptable graft positioning in both categories, yet a significantly steeper graft impaction angle was observed in the arthroscopic group. The long-term effects of the steeper graft position are not known (Ernstbrunner et al., 2018). One of the major advantages of the J-Bone technique is the absence of metal fixation devices, and consequently any complications related to hardware. A disadvantage is the perceived risk of graft loosening and the resulting reduced maximal pace of rehabilitation in the first postoperative weeks. However, a recent biomechanical study demonstrated excellent initial fixation rigidity, contact pressure distribution and restoration of glenohumeral stability using the J-bone construct (Pauzenberger et al., 2017).

A major concern in the use of anterior glenoid bone grafts, has been the development of early osteoarthritic changes in the shoulder. Some have attempted to counter this by interposition of the capsule between the graft and het humeral head, rendering the construct extra-articular (Steffen en Hertel, 2013). Others have been reassured by the spontaneous appearance of fibrocartilaginous tissue layer overlying the anterior glenoid bone grafts, even when the grafts are positioned intra-articularly (Auffarth et al., 2018). Alternatively, the transplantation of fresh osteochondral grafts has been explored. The most popular techniques include the transplantation of the autologous distal clavicle, or an allogeneic distal tibial graft. Both techniques have shown promise in short and mid-term follow-up (Tokish et al., 2014). A recent matched cohort study comparing distal tibia grafts to the Bristow-Latarjet procedure could not find any significant differences in outcome after a minimum follow-up of 2 years (Frank et al., 2018). However, longer-term follow-up is necessary to fully assess the risks and benefits of both techniques. Overall, the field of shoulder stabilization surgery is becoming wider and more nuanced. Where a “one size fits all” approach used to be the norm, nowadays we see the emergence of tailored surgical approach, based on the patient’s needs, the surgeon’s skills and the availability of materials and instruments. An illustration of the spectrum of surgical treatment possibilities on the glenoid side is given below (Fig. 6.2).

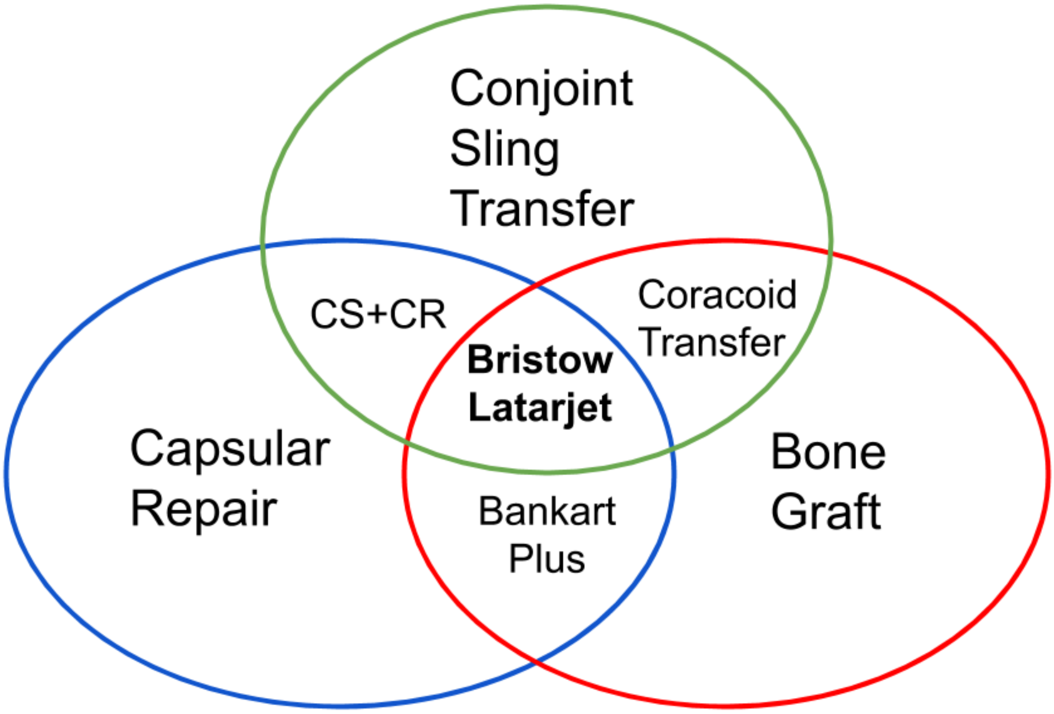

Figure 6.2
Venn diagram depicting the overlapping modalities of surgical interventions on the glenoid for anterior traumatic shoulder instability. Green circle encompasses all conjoint sling based techniques, blue circle represent all methods with a capsular repair component and red circle contains all bony surgical solutions. The Bristow-Latarjet procedure at the centre boasts a bony (coracoid), capsular (CAL) and conjoint sling part. The simple coracoid transfer procedure (such as most arthroscopic Bristow-Latarjet techniques) does not include a separate capsular reconstruction. The Bankart Plus method combines a bone graft and a capsular procedure (Moroder et al., 2018). The isolated conjoint sling (CS) transfer can be combined with a capsular reinforcement (CR) (Tennent et al., 2016).

6.2.5 Postoperative imaging

Until recently, postoperative imaging protocols have not received much attention. Standard radiographic follow-up usually consists of an immediate postoperative x-ray to assess graft position on the AP and Y-view, followed by successive x-rays at 6 weeks and 12 weeks to assess bony ingrowth and graft migration or breakage. Further follow-up is not typically performed, except in the context of research programs to evaluate the incidence of arthropathy and graft remodeling. Multi-axial advanced imaging may be of value in the closer appreciation of graft position and accuracy of surface reconstruction in the early postoperative phase, and in the reliable estimation of bony union between the graft and glenoid. In this respect, CT has been superior to MRI techniques in the visualization of bony healing and creating minimal distortion and artifacts due to the presence of metal hardware (Woertler, 2007). Conversely, the radiation incurred by repeated CT scans is usually not justifiable in a standard follow-up protocol. In the setting of postoperative pain or dysfunction however, CT becomes a powerful tool in the diagnosis of graft malpositioning in the coronal and sagittal plane, non-union, displacement, fracture, resorption and hardware prominence. Contrarily, soft-tissue complications such as fatty atrophy of the subscapularis or tendon tears may more easily be recognized on MRI. Much remains unknown about the postoperative evolution of anterior glenoid bone grafts after implantation, and in light of the importance of postoperative complications, more research into the best practice imaging guidelines is warranted.

6.3 Innovations

6.3.1 Fixation Techniques

The high incidence of hardware-related complications and reoperations has led to an increased interest in alternative bone graft fixation methods (Griesser et al, 2013)(Butt et al., 2012). An attractive solution has been the use of suture “button” devices for this purpose. These devices consist of two metal buttons linked by a self-tensioning suture. Various shapes and sizes exist, and are frequently used in the reconstruction of ligamentous injuries and tendon ruptures (Camp et al., 2016)(Förschner et al., 2017)(Yagnik et al., 2019). Bonnevialle and colleagues described their short-term results in 88 cases of arthroscopic double button Latarjet. The authors reported 3.3% intraoperative and 6.8% postoperative complications. All grafts were positioned flush and subequatorially, although migration was seen in 4.4% of cases. The study did warn about the technical difficulties of button fixation and suggested 30 cases were necessary to allow optimization of surgical time (Bonnevialle et al., 2018). Similarly, Boileau and colleagues presented their early results of a single-button retrograde drilling Bristow-like technique. The authors found correct positioning in 93% of the 75 patients, and a 91% healing rate. Moreover, the authors did not report any neurologic or hardware problems typical of screw fixation (Boileau et al., 2016). A similar technique has been described for use with free iliac crest bone grafts, although clinical results have not yet been published (Kalogrianitis et al., 2016). Biomechanical comparison of screws to double suture button fixation has not shown a significant difference in ultimate load to failure or strain before failure. Site of mechanical failure was different however, where screw constructs failed at the screw holes, suture buttons failed at the conjoint tendon-clamp interface (Provencher et al., 2018). The exact failure mechanism of coracoid transfers is not well understood however, and whether constructs should be tested by applying anteroposterior loads or supero-inferior traction via the conjoint tendon is disputed (Willemot et al., 2018).

6.3.2 Technique Modifications

As indications for surgery and differentiation of surgical strategy evolve, so do the surgical techniques. Recent studies have been published using only the coracoid sling without a bone graft (Tennent et al., 2016)(Dougouih et al., 2018), transferring only the coracoid tip (Tang et al., 2018) or transfering of the biceps long head instead of the short head to the glenoid neck (Collin et al., 2018). The objective added value of these particular surgical techniques has not yet been analyzed or compared to the gold standards such as Bankart repair or Bristow-Latarjet. Similarly, new techniques regarding bone grafting of the anterior glenoid and humeral head are published regularly. Recently, a method of transferring autologous distal femoral cartilage and bone was published (Ogimoto et al., 2018). However, long-term clinical studies will determine the viability of these new techniques.

6.4 Future Research Directions

It is often said that science never solves a question without creating ten more. This doctoral thesis is no exception. The work presented here has elucidated some areas of the treatment of anterior shoulder instability, yet leaves much uncertainty in regards to other aspects of bone block procedures. Despite the fact that much was learned from relatively basic biomechanical tests, we believe that future experiments will, at least in part, have to rely on virtual computer simulations of the shoulder girdle due to the complexity of the model. The recent explosion in open and arthroscopic stabilization techniques, utilizing a variety of grafts and fixation techniques will require extensive and thorough comparative testing. Moreover, some answers will only be gleaned from robust prospective double blind clinical studies.

In general, we are convinced that arthroscopic techniques which use a small free bone graft to reconstruct the inferior glenoid circle are the way forward in regards to the treatment of recurrent shoulder instability with a glenoid defect. However, instability treatment should be tailored to the needs of the patient with special attention to concomitant bony and soft-tissue lesions on the glenoid and humeral side. In the future we hope to further investigate the role of glenoid shape, including version and tilt, to perfect our bone grafting techniques. Furthermore, we hope to proceed with in-vivo clinical trials to evaluate the results of our surgical treatment protocols in a representative study population. Lastly, it is clear that fixation technology is emerging as an exciting and important player in the reduction of complications and improvement of outcomes in bone grafting procedures. Therefore, further biomechanical and clinical testing of these novel fixation devices and techniques will be valuable in the next generation of shoulder stabilizing procedures.

It has been said that understanding the problem is the first step to solving it. This doctoral thesis has, if anything, uncovered a great deal of unknowns in the area of anterior glenoid bone grafting for shoulder instability. We feel like this doctoral work has only scratched the surface, and much work remains to be done. Yet, it is only when we leave our proverbial hammer behind that we start appreciating that not everything looks like a nail.

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Abstract

Introduction

Traumatic anterior shoulder instability is a common problem with a significant burden on a young and active patient population. Recurrences, which are frequent after conservative treatment, are associated with discomfort, potentially dangerous situations, further injury to the local tissues and long-term degenerative changes to the shoulder. Surgical treatment may include soft-tissue treatment, bony intervention, or both. Traditional shoulder stabilization entails a repair of the torn capsule and labral structures. Alternatively, surgical treatment by addition of a bony anterior glenoid augmentation via coracoid or free bone graft has become increasingly popular. Capsulo-labral reconstruction is a well-tolerated procedure, yet predisposes the patient to a higher risk of recurrence compared to bone block procedures. Contrarily, bone block procedures are associated with a higher incidence of neurovascular injury, hardware-issues and graft-related complications. Ideally, a minimally invasive free bone graft augmentation would combine the benefits of the soft-tissue procedure and the robustness of the coracoid transfer. The exact biomechanical principles of bone block procedures in anterior shoulder stabilization surgery are not well understood.

Methods

The doctoral thesis is comprised of a literature review section defining what bone block procedures are. Next, a literature review was performed to evaluate the biomechanical evidence of bone grafting in anterior shoulder instability. We then, biomechanically, assessed the influence of anterior iliac crest grafting of an intact glenoid in a cadaveric specimen. Subsequently we investigated whether translational stiffness was predictable based on surface characteristics. We then performed a literature review of available bone grafts in the the setting of anterior glenoid bone loss and applied the findings of the surface analysis study to a cadaveric sample of bone grafts. Finally we also reviewed the failure mechanisms behind bone grafts and performed a biomechanical test of commonly used screws in bone graft fixation.

Results

The purpose of bone block procedures should not be to physically “block” dislocation, the name merely refers to the shape of the bone graft. These procedures encompass various types of coracoid transfers (i.e. Bristow and Latarjet) as well as free bone graft procedures (commonly referred to as Eden-Hybbinette). The procedures do attempt to reconstruct the anterior glenoid and stabilize the joint. Biomechanical studies have indicated that the addition of a conjoint sling dynamic stabilizer significantly increases the stabilizing effect of the procedure. We demonstrated biomechanically that the addition of a bone graft on the anterior glenoid would improve stability even in the absence of a glenoid defect. However, in view of later revelations regarding the risks of excessive bone grafting, this idea was abandoned. We did however, prove the predictability of joint stiffness by analysis of articular surface characteristics. Armed with these findings, we reviewed all graft options in the literature from coracoid based techniques to iliac crest, allograft distal tibia, glenoid and autogenous distal clavicle grafts. A morphological analysis of the most frequently used

constructs revealed a surprising underperformance of coracoid and tricortical iliac crest grafts, and a more favourable surface profile using novel graft sources. We also found an important role for symptomatic non-union after coracoid grafting in our revision of failed Bristow-Latarjets. A biomechanical analysis of various screw types used for graft fixation revealed important differences between the screws' fixation strengths based on screw design.

Discussion

The attractiveness of free bone grafting procedures is partly derived from the choice of available graft types, ease of graft harvesting, limited or absent donor morbidity, customizability of graft shape and size, possibility of simple all-arthroscopic techniques, graft passage through the rotator interval without disturbing the subscapularis muscle, and overall anatomic nature and minimal invasiveness of the procedure (Verborgt et al., 2015). In this doctoral thesis we explored some biomechanical and morphological facets of anterior glenoid bone grafting, as well as conducting a failure analysis and biomechanical investigation of hardware fixation. In combination with the findings from our literature review, the results of this doctoral work have led us to believe there may be an important role for free anterior glenoid bone grafts in anterior shoulder instability. Not only have we demonstrated biomechanical restoration of stability and morphological superiority. The clinical literature has indicated free bone grafts may perform just as well as coracoid based techniques with less risk of complications. We identified hardware as the main cause of complication and revision and our research demonstrated a significant difference in fixation strength between commonly used screws. In all confidence we can state that free bone blocks are a valid, and in some cases, preferred, alternative to traditional coracoid based anterior grafting techniques". However, further scientific exploration is required to evaluate the biomechanical and clinical behaviour of free bone block grafting in recurrent shoulder instability.

Samenvatting

Inleiding

Traumatische anterieure schouderinstabiliteit is een veelvoorkomend probleem met een belangrijke impact op een jonge en actieve patiëntenpopulatie. Herval, wat vaak voorkomt na conservatieve behandeling, is geassocieerd met pijn, mogelijks gevaarlijke situaties, lokaal weefseltrauma en degeneratieve veranderingen in het schoudergewricht op lange termijn. Chirurgische behandeling omvat herstel van de weke delen, beenderige structuren, of beide. Traditionele schouderstabilizerende technieken behelzen meestal een herstel van het labrum en schouderkapsel. Hiertegenover staat de recentere popularisatie van de beenderige technieken waarbij het glenoid wordt geaugmenteerd door middel van het ravenbeksuitsteeksel of een vrije botgreffe. Labrumherstel is een goed getolereerde ingreep, maar gaat gepaard met een hoger risico op herval, vergeleken met een beenderige procedure. Daartegenover staat dat beenderige augmentatie geassocieerd is met een hoger risico op neurovasculaire letsels en zowel greffe als fixatiemateriaal-gerelateerde problemen. Idealiter, zou een minimaal invasieve ingreep de voordelen van een weke delen procedure en de voorspelbaarheid van een beenderige techniek combineren.

Methoden

Deze thesis omvat een literatuurstudie die vooreerst definieert wat botblokprocedures zijn. Vervolgens werd een tweede literatuurstudie uitgevoerd met als doel de beschikbare data betreffende biomechanica van botblokprocedures te bestuderen. Hierna voerden we een biomechanische studie uit op kadavers met als doel de invloed van een anterieure beenderige greffe op schouderinstabiliteit na te gaan. Nadien werd vergeleken of translationele stijfheid van een gewricht kon voorspeld worden aan de hand van oppervlakte karakteristieken in een mathematisch model. Hierna werd een inventaris gemaakt van de, in de literatuur beschreven, greffes voor anterieure instabiliteit, en werden de bevindingen van onze oppervlaktestudie toegepast. Dit werd gedaan door middel van een morfologische studie op kadaverische specimen na reconstructie met verschillende anterieure botgreffen. Finaal werd ook een retrospectieve analyse van falingsmechanismen na coracoidtransplantaties uitgevoerd en onderzochten we ook biomechanische de rigiditeit van verscheidene klassiek gebruikte schroeven voor fixatie van botgreffes in schouderinstabiliteit.

Resultaten

Botblokprocedures hebben niet als oogmerk een ontwrichting te “blokkeren”. De naam refereert enkel naar de vorm van de beenderige greffes. Deze ingrepen omvatten transplantatie van het coracoiduitsteeksel (vb. Bristow en Latarjet) en vrije botgreffes (vaak gegroepeerd onder het eponym “Eden-Hybbinette”). De ingrepen hebben als doel de anterieure glenoidale rand te reconstrueren en het schoudergewricht te stabilizeren. Biomechanische studies hebben aangetoond dat de toevoeging van een dynamische sling de stabiliteit van de procedure significant verhoogt. Wij toonden, aan de hand van een biomechanische experiment, aan dat zelfs in afwezigheid van een anterieur botdefect, de toevoeging van een botgreffe de stabiliteit zou vergroten. Latere klinische observaties leerden ons evenwel dat het risico op complicaties bij suprafysiologische augmentatie van het glenoid te groot was om dit in de praktijk te kunnen toepassen. Alhoewel er hierdoor geen klinische implementatie mogelijk was van onze bevindingen, waren deze wel bijzonder behulpzaam in het ontwikkelen van een theoretisch model om translationele stijfheid te voorspellen op basis van oppervlaktekarakteristieken. Met deze kennis werd een inventaris opgemaakt van bruikbare greffe donoren zoals bekkenkam, distale tibia allogreffe, glenoid allogreffe en distale clavicula autogreffe. Een morfologische analyse van de meest frequent toegepaste greffes toonde een verrassend weinig accurate restoratie van de anterieure glenoidale rand met de klassieke coracoidale en tricorticale bekkenkamenten, en een meer passende oppervlakte reconstructie met nieuwere greffe types. De retrospectieve analyse van gefaalde Latarjet ingrepen toonde aan dat symptomatische pseudarthrosen een risico inhouden, evenals resorptie, trauma en malpositie van de greffe. De verdere uitdieping van dit risico door middel van een biomechanische analyse van fixatiestijfheid van verschillende traditioneel gebruikte schroeven, toonde het belang van schroef design aan. Schroeven met een groter verschil tussen diameter van de draad en de schacht, en een kortere schroefdraad, waren significant zwakker dan schroeven zonder deze eigenschappen in unicorticale constructies.

Discussie

De aantrekkelijkheid van vrije botgreffes berust op de diversiteit aan verschillende bruikbare greffes, the eenvoud in oogst en preparatie, de beperkte of afwezige donor morbiditeit, de personaliseerbaarheid in grootte en vorm van de greffes, de optie tot vereenvoudigde arthroscopische chirurgie, de mogelijkheid tot subscapularis sparende chirurgie, en een algemeen meer anatomische en minder invasieve procedure (Verborgt et al., 2015). In deze doctoraatsthesis onderzochten we een aantal biomechanische en morfologische aspecten van botblokprocedures, evenals een biomechanische investigatie van fixatietechnieken. Gecombineerd met de bevindingen uit de literatuur, heeft dit onderzoek ons ervan overtuigd dat er een belangrijke rol weggelegd is voor vrije botgreffe chirurgie in anterieure schouderstabilizerende chirurgie. Onze thesis toonde niet enkel biomechanische stabiliteit aan, maar ook een morfologische superioriteit van vrije greffes ten opzichte van de klassieke coracoidale en bekkenkamenten. Het doctoraatschrift identifieerde ook het fixatiemateriaal als een belangrijke bron van falen en revisie. Bijkomend werd ook een significant verschil in fixatiesterkte tussen veelgebruikte schroeftypes bij unicorticale schroefgrip. Tot conclusie kunnen wij stellen dat vrije botgreffes een valide alternatief, en in sommige gevallen mogelijks zelfs een eerste keuze, kunnen vormen bij de selectie van een stabilizerende botgreffe voor recidiverende anterieure schouderinstabiliteit. Desalniettemin, is verder biomechanisch en klinisch wetenschappelijk onderzoek noodzakelijk om de exacte rol van dit type greffes te bepalen binnen de indicatiestelling voor botblokprocedures en de behandeling van recidiverende anterieure schouderinstabiliteit.

Populaire samenvatting

Schouderontwrichting is een veelvoorkomend probleem met een belangrijke weerslag op de gezondheid en het dagelijks functioneren van de patiënten. Terugkerende ontwrichtingen, zogenaamde “instabiliteit” van het schoudergewricht komt vaak voor bij jonge mensen en actieve sporters. Heelkundig ingrijpen kan door de gewrichtsbanden terug te hechten waar deze van de rand van de kom van de schouder zijn afgescheurd. Uit studies is gebleken dat indien bepaalde factoren zoals jeugdige leeftijd, mannelijk geslacht, deelname aan contactsporten, en beenderige letsels van de bol of kom van het schoudergewricht aanwezig zijn, het risico op herval na deze ingrepen in belangrijke mate toeneemt. Een alternatieve vorm van chirurgie zijn de zogenaamde “botblokprocedures”. Uit onderzoek is gebleken dat dergelijke ingrepen wel degelijk de kans op herval verlagen, maar gepaard gaan met een groter risico op complicaties. Voornamelijk procedures waarbij het beenderig uitsteeksel onder het sleutelbeen geoogst wordt als greffe (het coracoid of ravenbeksuitsteeksel), zouden een hogere kans op lokale verwikkelingen met zich meebrengen.

Het doel van dit doctoraatsonderzoek was het nagaan of botblokprocedures die gebruik maken van een vrije botgreffe, in tegenstelling tot de klassieke coracoid gebaseerde technieken, een waardig alternatief vormen. Dit is van belang omdat vrije botgreffes een aantal unieke voordelen met zich meebrengen zoals beschikbaarheid, diversiteit aan types, meer mogelijkheden tot aanpassen van de vorm en zelfs kraakbeenbedekking in sommige gevallen. Een deel van deze onderzoeksvraag werd door middel van literatuurstudies beantwoord, en een deel door biomechanisch onderzoek op menselijke kadavers en kunststofmodellen.

Uit onze studies besloten we dat vrije botgreffes een waardig alternatief, en mogelijks in sommige gevallen zelfs eerste keuze, vormen tot de gebruikelijke coracoidgreffes voor de stabilizatie van terugkomende schouderinstabiliteit. Biomechanisch blijven de klassieke greffes een hogere graad van stabiliteit verschaffen door de transplantatie van de pezen verbonden aan de coracoidale greffe. Desalniettemin hebben we deels in de literatuur en deels in onze studies kunnen aantonen dat in de praktijk vrije botgreffes ook een voldoende stabilizerende effect zouden kunnen uitoefenen. Bijkomend hebben we aangetoond dat de vorm van de greffe van groot belang is in de correcte reconstructie van de kom van het schoudergewricht. Hierbij is de rijke keuze aan vrije botgreffes, sommige zelfs met kraakbeenbedekking, een belangrijke voordeel vergeleken met de klassieke greffes. Gezien de meestvoorkomende complicaties na botblokprocedures gerelateerd zijn aan het fixatiemateriaal dat gebruikt wordt om de blokjes aan de kom te verbinden, hebben we biomechanisch onderzocht of er een verschil in sterkte bestond tussen 3 veel gebruikte schroeftypes. Hieruit konden we afleiden dat afhankelijk van het ontwerp, en de lengte van de schroef, een significant verschil in sterkte van fixatie kon optreden.

Tot slot benadrukken we dat het schouderstabilizatie door middel van botgreffes een bijzonder actief onderzoeksgebied is waar in de laatste jaren een belangrijke evolutie heeft plaatsgevonden op vlak van indicaties en technieken. Wij verwachten in de toekomst een verdere evolutie naar chirurgische therapie op maat. Hierbij voorzien we een belangrijke rol voor arthroscopische technieken welke gebruik maken van een kleine vrije botgreffes voor de reconstructie van de rand van de glenoïdale kom.

Acknowledgements

First, I would like to express my sincere gratitude to Prof. Jan Victor and Prof. Olivier Verborgt for their continuous support and help in the writing of this thesis. Ever since the earliest days of my career, as an aspiring candidate with little to no experience in research or orthopaedic surgery, Prof. Victor and Verborgt have shown tremendous trust and confidence in my abilities. It was via their vast network of connections and thanks to their internationally respected scientific reputation that I was able to apply for a research fellowship position at the Mayo Clinic in Rochester Minnesota. In October 2012 I entered the Mayo Clinic biomechanical laboratory for the first time, in the footsteps of illustrious predecessors such as Prof. Eiji Itoi and Prof. Roger van Riet. Thus began my initiation in the world of musculoskeletal research. During this time at Mayo I was mentored by Dr. Kai-nan An, a legend of biomechanical research, whose enigmatic answers taught me to think critically and to doubt everything. During my first visit to Mayo, amongst many others, I also made the acquaintance of Dr. Joaquin Sanchez-Sotelo and Dr. Bassem Elhassan, who would prove to be incredibly helpful on the clinical side. It was thanks to them that I was able to apply for a second research fellowship at Mayo Clinic in 2015. I would like to thank Prof. Victor and Verborgt for their dedication and ongoing encouragement. Whether regarding fundraising, abstract submission, publication or speaking engagements, I have always been able to count on their unrelenting support and endorsement. I would also like to thank Prof. Roger van Riet, whose wit is almost as sharp as his surgical blade, for his guidance and help throughout my research fellowships and residency. Not only have these eminent researchers played a crucial role in my scientific and clinical development, they have also introduced me to their friends and families, and have made me feel like one of their own. I would also like to specifically acknowledge Dr. Bassem Elhassan, truly one of the world's greatest persons, for his endless kindness and hospitality, his inspirational creativity and his selfless teaching. And finally, I would like to personally thank Prof. Lieven De Wilde for accepting and relinquishing the promotorship of this thesis and guiding it towards its final conclusion. Thanks to his input, critical appraisal and helpful comments and suggestions, I believe we were able to elevate the quality of the thesis.

Secondly, I would like express my everlasting gratitude to my amazingly talented wife Nicole. Not only did she agree to accompany me to the frozen prairies of the American Mid-West on two occasions, she has also always been there for me in moments of discouragement and stress. Many have been the moments when the little free time I had, was taken up by conferences or late night writing bouts. However, the two years we spent in Minnesota were the beginning of a great adventure. It was in Rochester that we met some of the people that have become amongst our closest and best friends. Sarah, Loribeth, Ryan, Elizabeth, Grady, April, Cesar, Mohsen, Suenghan, Shaun, Andrew, Andy, Larry … I can't even begin to count the great moments we shared. Thanks to their help and expertise, I was able to improve my writing skills, my understanding of biomechanics, statistics and scientific experiments, not to mention mountain biking and gravel racing. It was in Rochester that our first son, Benoît, was born. Due to his gastroschisis, we had the opportunity of being on the receiving end of patient care at Mayo Clinic. And despite the many sleepless nights and

tumultuous weeks in the neonatal intensive care ward, we could only be humbled by the magnificent work performed by the Clinic's staff. The Mayo motto "the patient comes first" is truly respected in all aspects of patient care.

Finally, I would like to thank my parents for their enduring love and support. If it wasn't for their parenting skills and foresight, none of this would ever have been possible.

Appendix

Appendix 1: Curriculum Vitae

Curriculum Vitae

Personal Information

Surname:	Willemot
Given name:	Laurent
Gender:	Male
Marital status	Married to Nicole Declerck
Children	Benoît and Sebastian Willemot
Date of birth:	02/04/1986
Place of birth:	Ghent
Email:	laurent.willemot@ugent.be

Schooling and studies

High School:	St-Barbaracollege Ghent	
	Main topics: Greek and Sciences.	
University:	Medicine at Ghent University	
	Bachelor of Medicine in 2004-2007:	790/1000
	Master of Medicine in 2007-2011:	800/1000

Languages

Dutch: Native Speaker

English:	Thorough knowledge (TOEFL 115/120)(IELTS Band 8.5)
French:	Thorough knowledge
German:	Basic knowledge
Italian:	Basic knowledge

Academical

Fellowship in Hand Surgery And Peripheral Nerve Surgery

Royal North Shore Hospital, Sydney, AU

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Residency St. Lucas, Bruges, Belgium

01/10/16 - 30/9/17:

Mayo Clinic Research Fellowship with dr B. Elhassan

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Residency University Hospital, Ghent, Belgium

01/10/13 - 30/9/14

Research Fellowship at Mayo Clinic Rochester, MN, USA

01/10/12-01/10/13

Residency AZ Damiaan, Ostend, Belgium

01/08/11- 01/10/12

Overseas development

NPH Mission in Phnom Penh, Cambodia with Belgian hand surgeons

February 2018

NPH Mission to Preah Vihear provincial hospital in Cambodia

April 2015

NPH Phnom Penh National Pediatric Hospital visiting surgeon.

December 2013

Three month clerkship in Cambodja (Siem Reap and Phnom Penh)

March-June 2011

Publications

Taming hard problems with soft tissues?
Willemot L., Verborgt O.
Editorial Commentary Arthroscopy
The role of soft tissue reconstruction after failed Bristow-Latarjet. Lavoué et al., 2019. Unpublished.

Willemot, L., De Boey, S., Van Tongel, A., Declercq, G., De Wilde, L., & Verborgt, O. (2019). Analysis of failures after the Bristow-Latarjet procedure for recurrent shoulder instability. *International Orthopaedics*, *43*(8), 1899–1907. https://doi.org/10.1007/s00264-018-4105-6

Willemot, L., Hendrikx, F. R., Byrne, A.-M., & van Riet, R. P. (2018). Valgus instability of the elbow: acute and chronic form. *Obere Extremitat*, *13*(3), 173–179. https://doi.org/10.1007/s11678-018-0465-1

Willemot, L. B., Elhassan, B. T., Sperling, J. W., Cofield, R. H., & Sanchez-Sotelo, J. (2018). Arthroplasty for glenohumeral arthritis in shoulders with a previous Bristow or Latarjet procedure. *Journal of Shoulder and Elbow Surgery*, *27*(9), 1607–1613. https://doi.org/10.1016/j.jse.2018.02.062

Willemot, L. B., Akbari-Shandiz, M., Sanchez-Sotelo, J., Zhao, K., & Verborgt, O. (2017). Restoration of Articular Geometry Using Current Graft Options for Large Glenoid Bone Defects in Anterior Shoulder Instability. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : Official Publication of the Arthroscopy Association of North America and the International Arthroscopy Association*, *33*(9), 1661–1669. https://doi.org/10.1016/j.arthro.2017.04.002

Willemot, L. B., Elhassan, B. T., & Verborgt, O. (2018). Bony Reconstruction of the Anterior Glenoid Rim. *The Journal of the American Academy of Orthopaedic Surgeons*, *26*(10), e207–e218. https://doi.org/10.5435/JAAOS-D-16-00649

Willemot, L. B., Wodicka, R., Bosworth, A., Castagna, A., Burns, J., & Verborgt, O. (2018). Influence of screw type and length on fixation of anterior glenoid bone grafts. *Shoulder & Elbow*, *10*(1), 32–39. https://doi.org/10.1177/1758573217704817

3D printed guides for controlled alignment in biomechanics tests.
Verstraete MA, Willemot L, Van Onsem S, Stevens C, Arnout N, Victor J.
J Biomech. 2016 Feb 8;49(3):484-7. doi: 10.1016/j.jbiomech.2015.12.036. Epub 2015 Dec 29.

Radiological and clinical outcome of arthroscopic labral repair with all-suture anchors. Laurent Willemot. Redouan Elfadali Kjell C Jaspars Mark H Awh Jeff Peeters Nick Jansen Geert Declercq Olivier Verborgt. Acta Ortopedica Belgica. 2016, N° 2 (Vol. 82/2) p.174-178

Revision of a Failed Latarjet Procedure using an Open Tricortical Iliac Crest Autograft Technique. Willemot, Laurent MD; Declercq, Geert MD; Verborgt, Olivier MD, PhD. Techniques in Shoulder & Elbow Surgery. September 2015Vol. 16 - Issue 3: p 69–73

Willemot, L., Thoreson, A., Breighner, R., Hooke, A., Verborgt, O., & An, K.-N. (2015). Mid-range shoulder instability modeled as a cam-follower mechanism. *Journal of Biomechanics*, *48*(10), 2227–2231. https://doi.org/10.1016/j.jbiomech.2015.02.053

Graft Position Determines Stability in Free Bone Graft Augmentation Procedures of the Anterior Glenoid. Willemot L., Eby S., Thoreson A., Victor J., An KA., Verborgt O. J Shoulder Elbow Surg. 2014 Nov 12. pii: S1058-2746(14)00517-5. doi: 10.1016/j.jse.2014.09.018.

Accuracy of the glenohumeral subluxation index in non-pathological shoulders. Matthijs Jacxsens, M.D.; Alexander Van Tongel, M.D., PhD; Laurent Willemot, M.D.; Victor Valderrabano, M.D., PhD; Andreas M Müller, M.D.; Lieven De Wilde, M.D., PhD. J Shoulder Elbow Surg. 2014 Oct 22. pii: S1058-2746(14)00464-9. doi: 10.1016/j.jse.2014.07.021.

Anterior Hip Replacement.
Pagnano MW, Willemot L. The journal of bone and joint surgery. Orthopaedic Crossfire. Supplement. Vol. 95-B, No. 11, November 2013.

A 24-Month Follow-up Study on Clinical and Radiological Outcomes of Polyurethane Meniscal Scaffolds
De Coninck T, Huysse W, Willemot L, Verdonk R, Verstraete K, Verdonk P.
Am J Sports Med. 2013 Jan;41(1):64-72. doi: 10.1177/0363546512463344. Epub 2012 Nov 1.

Case Report: Cephalohematoma at birth. Willemot L1, Lagae P. [1], Jeannin P.[2], Baelde N.[1], Verstraete K.[3] JBR-BTR. 2013 Jul-Aug;96(4):258-9.

Presentations

Complex Shoulder Instability
Shoulder Session, Orthopedica Belgica 2019.

Orthopedic Scores in Shoulder Instability.
Young Forum Session SECEC 2018.

Arthroplasty for Glenohumeral Arthritis in Shoulders with A Previous Bristow or Latarjet Procedure
Presented by dr J. Sanchez-Sotelo at AAOS 2018..

Basic Principles:Biomechanics of shoulder instability. BVOT Fall course Antwerp, december 2017.

Biomechanical aspects of bony-mediated shoulder instability and treatment implications.
SECEC 2017 symposium.

Influence of screw type and length on fixation of anterior glenoid bone grafts.
Poster SECEC 2018.

Distal Tibia And Glenoid Allografts Are Best For Restoration Of Overall Glenoid Congruency In Scapulae With An Anterior Glenoid Rim Defect
Closed meeting SECEC 2016
Closed meeting ASES 2016 (presented by Dr. Verborgt O.)
AAOS meeting 2017
Open SECEC meeting 2017

Clinical and radiographic analysis of failed Bristow-Latarjet procedures for recurrent shoulder instability
Poster presentation at SECEC 2015 in Milan.
Presented at ISAKOS 2015 in Lyon.
Speaker at Ghent University Resident's Day 2015

Glenohumeral stability is increased after iliac crest grafting with optimal graft positioning.
Graft Position Determines Stability in Free Bone Grafting Procedures.
Speaker and Poster Presentation at SECEC 2014.

Speaker, demonstrator and moderator during live surgery sessions. at the Ghent University Surgical Summer School 2014: "Orthopaedic Residency".

Case presentation at Belgian Elbow and Shoulder Surgery (BELSS) meeting. Recurrent shoulder instability after Latarjet procedure.

Graft Position Determines Stability in Free Bone Grafting Procedures.
Speaker resident day Pellenberg 2014.

Shoulder Instability as a Cam-follower Mechanism
Willemot L. Eby S. Thoreson A., Verborgt O. An KA.
Poster presentation at ORS 2014, New Orleans.
Poster presentation at EORS 2014, Nantes. Best Poster Award.

Graft Position Determines Stability in Free Bone Graft Augmentation Procedures of the Anterior Glenoid
Willemot L., Eby S., Thoreson A., Victor J., An KA., Verborgt O.
Podium Presention at AAOS 2014, New Orleans.

Poly-urethane scaffold for the treatment of medial and lateral partial meniscus defects: A single center experience with focus on scaffold integrity.
P.C. Verdonk, L. Willemot, P. Beekman, R. Verdonk, Gent/BE
Podium presentation at ESSKA conference in Genève, May 2012.

Webinars

Webinar JAAOS Plus. Bony Reconstruction of the Anterior Glenoid Rim.
Willemot LB, Elhassan BT, Verborgt O. May 15th 2018.

Video

What to do with a B2. AAOS Video corner, Las Vegas, 2019.

Elbow Arthroscopy in Acute and Chronic Instability. SECEC Video, Geneva 2018.

What to do with a B2. SECEC and AAOS video.

Keystone flap. AAOS video, New Orleans 2018.

Arthroscopic Distal Clavicle Resection. AAOS video New Orleans 2018.

Arthroscopic fixation and bone grafting of scaphoid non-union. Presented at AAOS 2017, San Diego.

New Technique for Acetabuloplasty in Legg-Calve-Perthes disease. Presented at AAOS 2016, Orlando.

Revision of a failed latarjet by iliac crest bone grafting (Eden-Hybinette). Video accepted for SECEC 2014 and AAOS 2015 presentation.

Awards

SECEC Didier-Patte Prize for best Doctoral Thesis

September 2019

Belgian Association for Orthopedic and Trauma Surgery (BVOT) research grant. March 2019.

Belgian American Educational Foundation (BAEF) Post-doc fellowship award 2015.

Fulbright Commission Award fellowship 2015.

Graft Position Determines Stability in Free Bone Grafting Procedures.
Selected for national societies best national paper SECEC 2014.
Best Poster: EORS 2014, Nantes. Shoulder Instability as a Cam-follower Mechanism. Willemot L. Eby S. Thoreson A., Verborgt O. An KA.

Runner up “Basic Science Excellence” award for publications in Journal of Arthroscopy regarding the article: *Restoration of Articular Geometry Using Current Graft Options for Large Glenoid Bone Defects in Anterior Shoulder Instability*. Award Winning Research Recognized
Jefferson C.BrandM.D.(Assistant Editor-in-Chief)Michael J.RossiM.D.(Assistant Editor-in-Chief)James H.LubowitzM.D.(Editor-in-Chief)
https://doi.org/10.1016/j.arthro.2017.11.007.

Appendix 2: Signed title page D. Sedaris