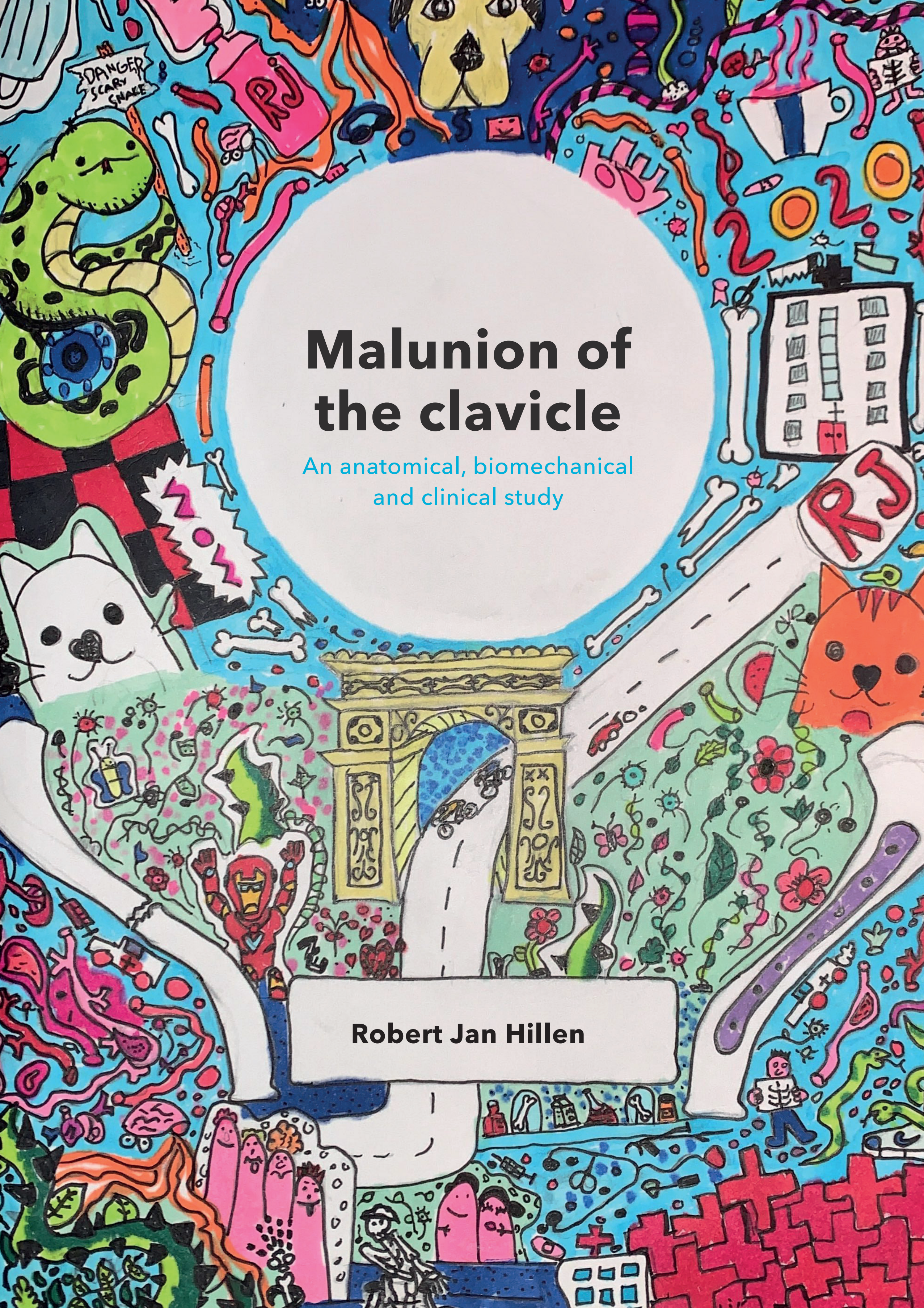

Malunion of the clavicle

An anatomical, biomechanical and clinical study

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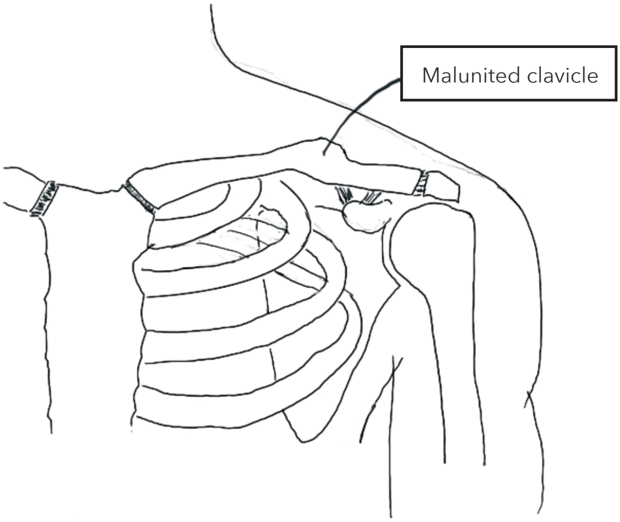
Chapter 1

General introduction

Clavicular malunion is a common phenomenon which occurs when a clavicular fracture heals in a non-anatomic position and thus results in a united fracture but an altered shape of the affected bone. Malunion can occur in 3 directions: In the frontal plane, transverse plane and rotation and can be with or without shortening.



Around 400 B.C.E. Hippocrates already wrote that in case of a fracture of the clavicle, correct reduction of the fracture (ascertaining an anatomical outlining of the fractured parts) is most of the time impossible to achieve or to maintain and mentioned that the healing process following the fracture often results in a malunion. He did not see malunion as a serious problem, stating: "When a fracture has recently taken place, the patients attach much importance to it, as supposing the mischief greater than it really is." (Hippocrates 2002) We can assume that in those days he was right because the treatment options were limited and the expectation of treatment outcome likely also did greatly differ from today. With the introduction of plate osteosyntheses in the late 1940's a new treatment option for fractures of the long bones was available. For the treatment of displaced mid-shaft clavicular fractures, however, traditional teaching has been that conservative treatment results in a good outcome in the vast majority of patients. The incidence of symptomatic malunion after mid-shaft clavicle fracture has been estimated to be around up to 30% (Hillen et al. 2010).

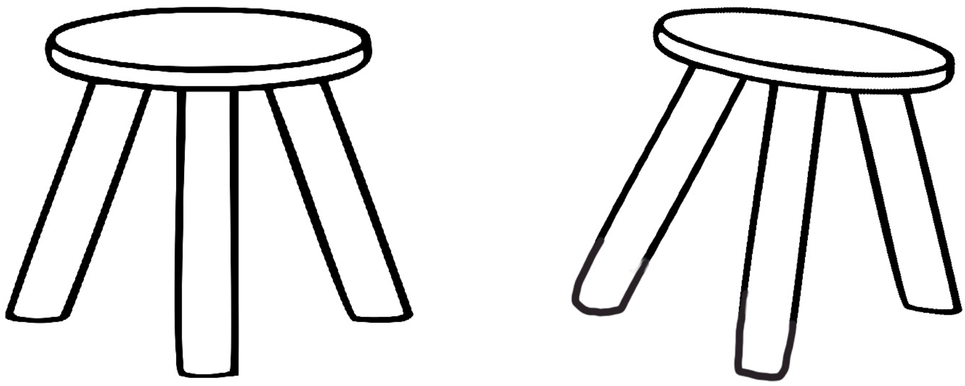
Research by Neer(1960) and Rowe(1968) in the sixties, in which the outcome of a large number of conservatively treated clavicle fractures was analyzed, formed the basis for opinion that for displaced fractures malunion of the clavicle with shortening, and possibly also rotational deformity, will be an acceptable outcome. Surgical treatment has for a long time been reserved for open fractures or fractures with neurovascular damage. The acceptance of malunion as outcome of fracture treatment is not common in any of the other long bones in humans. Since the clavicle is the only long bone in which malunion is considered an acceptable outcome for most patients the question raises whether malunion after a mid-shaft clavicle fracture is really not a cause of any problems or complaints (sequalae).

Neer and Rowe concluded that conservative treatment was a successful treatment based on the high number of united fractures and the resulting range of motion of the shoulder. When looking at those studies from today's perspective, one has to conclude that they have a low level of evidence and show methodological errors. These studies made no distinction between children and adults and discarded an important factor that we now consider: the outcome experienced by the patient. Later studies showed that reporting in patient-based outcome scores severely changes the outcome of conservative treatment. This severe change can also be seen with looking at the adult group separately (Robinson 1998; Nowak et al. 2005).

In the last decades the results of the functional outcome after surgical fracture treatment have risen, the downsides of operative treatment such as infection risk have decreased, and we have better implants for fracture fixation available today. Risks related to surgical treatment of mid-shaft clavicular fractures were overrated (Altamimi and McKee, 2008; Kloen et al. 2009) while the incidence of sequelae or non-union after conservative management of a mid-shaft clavicular fracture have been underestimated (McKee et al. 2006; Robinson 1998; Robinson et al., 2004). In the last 2 decades this view has changed. The first study mentioning poor outcome after conservative treatment of mid-shaft clavicle fractures with shortening of more than 1,5 cm was by Eskola et al (1986) and this article has been cited 172 times since. The article by J.M. Hill et al. published in 1997 was titled "Closed treatment of displaced middle-third fractures of the clavicle gives poor results". This paper was probably the first to debate the conservative treatment for all clavicle fractures. It has been cited 514 times so far and so we can regard his message induced an important change in the way that we look at mid-shaft clavicle fractures. More and more osteosyntheses is performed for displaced mid-shaft clavicle fractures. A shift from conservative treatment to operative treatment will prevent malunion but has its own downsides. Risk of surgical complications, a second operation for hardware removal need to be considered. The cost of treatment is to be considered as well. Althausen et al.(2013) have shown that operative treatment can be cost effective although Nicholson et al (2019) showed the margins to be very small. As mentioned before symptomatic clavicle malunion occurs in up to 30% (Hillen et al. 2010) of the cases so if we operate all displaced mid-shaft clavicle fractures we will only prevent malunion in less than one third of the cases.

For this thesis we looked further into the subject of clavicle malunion. The literature on the subject has been focusing on the incidence of malunion after mid-shaft clavicle fractures and the incidence of symptomatic malunion as well as describing the symptoms. Only a few efforts were made in explaining the underlying mechanisms that might explain the development of symptomatic clavicle malunion (Ledger et al. 2005; Patel et al 2012). Not all patients with a malunion report symptoms, so understanding the changes in biomechanics that occur with shortening of the clavicle are of importance to select the patient at risk for symptomatic malunion in an early stage. The magnitude of shortening in a clavicle malunion has many times been named a crucial factor for developing a symptomatic malunion. Why shortening would lead to symptoms is however not clear.

One of the factors that could be the cause of symptoms after malunion is alteration of the mechanical balance around the shoulder due to the altered shape of the clavicle. The clavicle acts as a strut for the shoulder girdle. Like a pair of compasses, together with the scapula medial border, it defines the trajectory along which the scapula can move. Shortening of the clavicle will alter the orientation of the scapula and upper extremity with regard to the rest of the skeleton and diminish the radius of the scapular tract. Because the scapular motion is also defined by the shape of the thorax, shortening of the clavicle will lead to kinematic changes at all levels of this closed system. Just like with a three-legged stool shortening of one leg will cause new stable position but the seat will no longer be horizontal. Shortening will by definition change the anatomy and will thereby alter the biomechanical properties of the shoulder girdle. We would expect changes in maximal muscle moments on muscles working over the (shortened) clavicle. The muscles themselves will also have different working lengths.



This thesis tries to come to a better insight as to what the consequences of malunion of the clavicle are. It will do so from different perspectives. Clinical studies were performed as well as a literature study and biomechanical studies. We tried to better define the malunion of the clavicle in terms of, incidence, symptoms and alteration of biomechanics, risk of symptomatic malunion after a fracture, causes of symptomatic malunion of the clavicle and treatment options available.

In Part I: *The current view on clavicle malunion*

A literature study is presented in **chapter 2:** An analysis of the currently available literature on the subject of clavicular malunion. Aim of this study was to determine whether short malunion of the clavicle is acknowledged as a cause of shoulder complaints, if there is literature on the causes of these complaints and if treatment strategies have been described. A thorough review of the limited current literature on the subject of clavicle malunion after mid-shaft clavicle fractures was done. In **chapter 2** we describe the anatomy, trauma mechanism, classification, epidemiology and incidence of malunion, prevention of malunion and symptoms of malunion. Treatment options and outcome for symptomatic malunion are also described. With input from the reviewed literature we proposed an algorithm for treatment of mid-shaft clavicular fractures. By using patient and fracture characteristics this algorithm helps making a choice whether to favor conservative or operative treatment in case of a displaced mid-shaft clavicle fracture.

In Part II: *experimental studies*

Two experimental studies are presented. These studies have been designed for describing what changes in the shoulder girdle as a result of shortening of the clavicle. The clavicle is the only bony connection of the shoulder girdle to the rest of the skeleton. The strut function, as mentioned earlier, cannot be maintained in the same manner when the clavicle is shortened. Shortening the length of the clavicle with an unchanged outline of the thorax will force the scapula to alter its normal pathway and with that will change the geometry of the system and as a consequence also alter the way the muscle forces are exerted on the shoulder girdle. Other studies have described these changes in resting position but few focused on changes during motion of the shoulder. To our opinion no previous study has described these changes during motion correctly. With knowledge of these changes we hope to clarify why shortening can cause symptoms. **Chapter 3** describes the changes that take place in the bony alignment of the shoulder girdle as a result of experimental shortening of the clavicle in a cadaveric study. In **chapter 4** the data from the cadaveric study in chapter 3 are processed in a computer model of the upper extremity to study the effect of clavicular shortening on potential muscle of the shoulder girdle.

Part III: *The Clinical studies*

Clinical studies (**chapter 5, 6,7 and 8**) on the subject of clavicle malunion were conducted to investigate the risk of a clavicular malunion to become symptomatic and whether a symptomatic malunion can be treated.

In **chapter 5** we retrospectively analyzed a consecutive group of conservatively treated mid-shaft clavicular fractures to see what patient characteristics can be isolated as a predictive factor for developing complaints after union of the fracture. We also looked at the incidence of symptomatic malunion. What can we learn from a retrospective look at initial presentation now we know what patients have developed a symptomatic malunion?

In **Chapter 6** we re-examined the patient group from chapter 5 to see if patient outcome would change in time with a longer follow up. From the outcome in chapter 4 we would expect these patients to have diminished strength. We measured strength difference between left and right to see if our in vitro findings could be confirmed in vivo.

In **chapter 7** we analyzed the effect of a correction osteotomy of a symptomatic mid-shaft clavicular malunion. If patients have a symptomatic malunion does reconstructing the clavicle to its original length relieve these symptoms? A retrospective study was done to analyze the effect of correcting a malunion to its original length.

In **chapter 8** we describe a suggested technique to perform correction osteotomy of malunion after mid-shaft clavicle fracture together with the first results of this new technique.

Part IV: *Discussion, summary and conclusions*

Chapter 9 is a general discussion on the research presented in this thesis. In **chapter 10** there is a summary and conclusion in English and in Dutch.

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Chapter 2

Malunion after mid-shaft clavicle fractures in adults

Current view on clavicular malunion in the literature

Hillen RJ, Burger BJ, Pöll RG, Gast A De, Robinson CM. Malunion after mid-shaft clavicle fractures in adults The current view on clavicular malunion in the literature. Acta Orthop. 2010;81(3):273-279.

Abstract

The view on mid-shaft clavicle fractures has changed in the last 15 years Adult patients with a displaced fracture have a higher number of non-unions than previously expected. Secondly the outcome after union is now measured with patient-based outcome scores which detects subtle loss of function in daily activities. Displaced fractures heal with some degree of shortening and therefore result in malunion (or non-union) unless treated operatively. Malunion can become symptomatic with pain, loss of strength, rapid fatigability, numbness or paraesthesiae of the arm and hand, problems with sleeping on the back as well as cosmetic complaints. Several mechanisms have been suggested as responsible for these problems after malunited mid-shaft clavicle fractures. Treatment can be either prevention in the acute phase by means of primary osteosyntheses or later when the symptomatic malunion is established, a correction osteotomy can be performed.

Introduction:

The shoulder is a closed chain mechanism and constitutes the combined function of four joints: The sternoclavicular-, the acromioclavicular-, the scapulothoracic- and the glenohumeral- joint (Veeger and van der Helm, 2007). The function of each individual joint differs from the other three but the function of these four altogether is so intimately related that it is impossible to treat one of the constituents of the shoulder joint without influencing the mechanism of the others (Inman and Saunders, 1946). Two out of the four joints are articulations of the clavicle therefore clavicle malunion must affect the whole shoulder girdle. Symptomatic malunion after mid-shaft clavicular fractures has been recognized in the last 15 years as a cause of shoulder dysfunction. Several authors have reported about this condition (Eskola et al., 1986,Hill et al., 1997,Lazarides and Zafiropoulos, 2006,Ledger et al., 2005,McKee et al., 2003,Nowak et al., 2004,Zlowodzki et al., 2005). Because reports about treatment of clavicular malunion with restoring the length of the clavicle show good results (Basamania C.J., 1999,Bosch et al., 1998,Chan et al., 1999,Hillen and Eygendaal, 2007,McKee et al., 2003,McKee et al., 2004,Rosenberg et al., 2007,Simpson and Jupiter, 1996), this condition should be considered as a distinct clinical entity. In this review we make an analysis based on the current literature available on clavicle malunion. Because of the limited amount of specific publications available on the subject and low level of evidence it is not a systematic review but rather a current concepts study. Epidemiology of malunited mid-shaft clavicle fractures will be mentioned as well as when to consider prevention of malunion of an acute mid-shaft clavicular fracture, and when to treat a symptomatic malunion after a conservative treated fracture of the clavicle mid-shaft. The treatment options and possible complications will also be summarized.

Anatomy

The clavicle is a S shaped long bone with a cephalad caudad curvature (Andermahr et al., 2007,Huang et al., 2007). Attached to the medial side is a part of the sternocleidomastoid muscle. On the lateral side part of the deltoid and pectoralis major muscles are attached. The mid-shaft part of the clavicle is a transition zone between the flattened shape of the lateral part and the more tubular to triangular shape medial. It is the thinnest segment of the clavicle and is not stabilized by ligaments. The lateral as well as the medial side of the clavicle are, unlike the mid-shaft, stabilized by strong ligamentous as well as muscular structures. The mid-shaft is left relatively unprotected; therefore, the majority of clavicle fractures are in the mid-shaft (Moseley, 1968, Rowe, 1968).

Trauma mechanism

A fall onto or a direct blow on the shoulder giving an axial compressive force on the clavicle is the most common mechanism of injury for any clavicle fracture. Another less frequent cause of clavicular fractures is a direct trauma onto the clavicle (Nowak et al., 2000,Stanley et al., 1988). Other mechanisms have been described but are rare, often as part of a more severe injury such as a floating shoulder (van Noort and van der, 2006). The mid-shaft or Edinburgh type 2 fractures tend to shorten when displaced (Edinburgh type 2B fractures). The displacement and in turn shortening is caused by unopposed muscular forces that occur when the shaft of the clavicle is fractured. Displacement of mid-shaft clavicular fractures is caused by the combined working of the sternocleidomastoid muscle pulling the medial fragment superiorly and posteriorly, and the pectoralis major muscle, the deltoid muscle and gravity pulling the lateral fragment inferiorly and anteriorly. The net effect is a displacement of the fracture ends relative to each other, with the lateral fragment lower than the medial fragment. The actual shortening in turn is caused by the medializing force components of the pectoralis, the trapezoid and the latissimus dorsi muscles pulling the shoulder girdle medially. The shortening therefore is in our view an ongoing process after a displaced fracture although there is evidence that the amount of shortening between the first presentation of the fracture and (mal)union does not change significantly (Smekal et al., 2009). Other authors do see a difference between initial shortening and the amount after (mal)union (Hill et al., 1997).

Classification

Several classification systems have been suggested for clavicular fractures. The Edinburgh classification as suggested by Robinson (Khan et al., 2009,Robinson, 1998)(fig 1) is gaining popularity in the literature and deals with the whole clavicle but is specific enough to deal with the specific problems for each segment. This paper will deal with the displaced mid-shaft or type 2B fractures. The Edinburgh classification system is the most valuable in terms of choosing therapy as well as being of prognostic value for mid-shaft clavicular fractures. In the Allman classification the clavicle is divided into three sections and numbered according to fracture incidence (mid-shaft I, lateral II, medial III) (Allman, Jr., 1967). This classification gives little information for choice of treatment or expectations on outcome. In this article we only discuss the Allman type 1 fractures. The orthopaedic Trauma Association suggested a classification (, 1996) in which the amount of fragments would determine the classification of a midmshaft fracture; varying from type A for simple fractures to type C for comminuted fractures. This classification system is not widely used for clavicle fractures. The classification systems as suggested by Neer (1963) and Craig (1990) are amendments on the Allman classification and are not of interest for mid-shaft fractures.

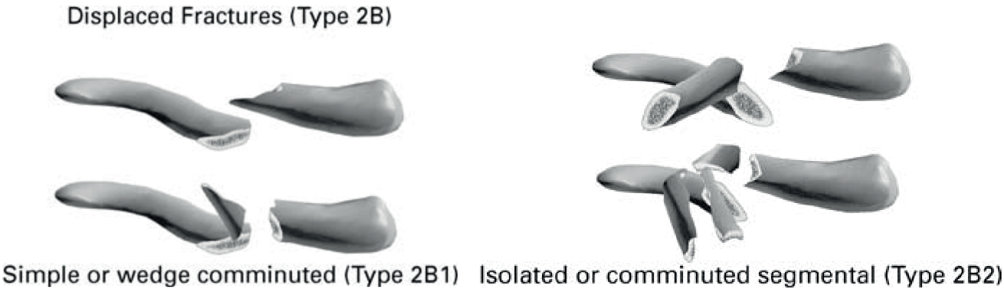

Figure 1. The displaced mid-shaft fractures in the Edinburgh Classification for clavicle fractures

Table 1. Overview of results on corrective osteotomy after mid-shaft clavicle malunion

Study	Nr of patients	Average follow up (month)	Type of scoring	Average pre op	Average post op	Plate removal	Complications nr
Bosch et al., 1998	4	24	Constant-Murley	?	C-M 89	?	0
Chan et al., 1999	4	24	Surgeons evaluation	?	?	3	0
Hillen and Eygendaal, 2007	10	37	DASH	DASH 78	DASH 45	7	2
McKee et al., 2003	15	20	DASH	DASH 32	DASH 12	2	1
Rosenberg et al., 2007	2	41	Constant-Murley	?	C-M 56	?	?
Basamania C.J., 1999	9	>3	Surgeons evaluation	?	?	all (pin)	0

Mid-shaft clavicle fractures epidemiology / Incidence of malunion after mid-shaft fracture

Clavicle fractures are common fractures with an incidence up to 5% of all fractures in adults (Nordqvist and Petersson, 1994,Nowak et al., 2000,Postacchini et al., 2002,Robinson, 1998) between 69 and 82 % of these are mid-shaft fractures (Khan et al., 2009,Robinson, 1998). Displacement occurs in about 73% (Khan et al., 2009,Robinson, 1998) of the mid-shaft clavicle fractures and the amount of non-unions is about 5% but can be much higher in the group with displaced fractures

(Khan et al., 2009,Robinson, 1998,Robinson et al., 2004) so of all mid-shaft clavicle fractures about two-third will end up to have some degree of malunion. Average shortening after a displaced fracture is about 1.2 cm with a range up to 3 cm (Eskola et al., 1986,Hill et al., 1997,Nordqvist et al., 1997). Shortening of more than 1.4 to 2 cm has been reported as a critical deficit for developing a symptomatic malunion (Eskola et al., 1986,Hill et al., 1997,Lazarides and Zafiropoulos, 2006,Nowak et al., 2004,Nowak et al., 2005,Postacchini et al., 2009).

Prevention of malunion after mid-shaft fracture in the acute phase both conservative and operative

Nonoperative treatment: Numerous closed treatment options have been described to immobilize and possibly re-align the dislocated fracture and help maintaining the alignment but almost all authors, to as far back as Hippocrates, state that maintaining the alignment after closed reduction of a displaced mid-shaft clavicle fracture is wishful thinking (Adams CF, 1939,Andersen et al., 1987,Khan et al., 2009,Lester CW, 1929). Methods that are still used to date are a simple sling or a figure of eight bandage where the last has been reported as being less comfortable and giving no advantage over to the simple sling (Andersen et al., 1987,Zlowodzki et al., 2005). This means conservative treatment of a simple mid-shaft clavicle fracture should be with a simple sling (Andersen et al., 1987,Eskola et al., 1986,Khan et al., 2009,Nordqvist et al., 1998) however there is no conservative measure to prevent a malunion after a displaced mid-shaft clavicle.

Operative treatment: The only way to prevent a malunion in a dislocated mid-shaft clavicle fracture an open reduction with internal fixation or a per cutaneous procedure. We will discuss the two types of fixation that are most commonly used: Plate fixation and intramedullary fixation.

Plate osteosyntheses has been reported as a successful procedure for acute mid-shaft clavicular fractures many times (Zenni, Jr. et al., 1981,Shen et al., 1999,Russo et al., 2007,Rowe, 1968,Poigenfurst et al., 1992,Nowak et al., 2004,Nowak et al., 2005,Mullaji and Jupiter, 1994,Coupe et al., 2005,Collinge et al., 2006,Bostman et al., 1997) and there is debateable evidence that primary open reduction and internal fixation by means of plate osteosyntheses might be superior to primary closed treatment (Canadian Orthopaedic Trauma Society, 2007). Plate osteosyntheses has the advantage of restoring length and alignment anatomically and It is biomechanically the strongest implant. Disadvantages are that it is more invasive compared with intramedullary options. Complications seen with plate osteosyntheses are infection, implant failure, implant loosening, re-fracture after implant removal and less frequent scar related problems and non-union (Bostman et al., 1997,Khan et al., 2009,Smekal et al., 2008). A recent prospective randomized trial reported an incidence of adverse events of 37% however the complication percentage in the non-operative group was 63% (Canadian Orthopaedic Trauma Society, 2007). Hardware needs to be removed in about 30% after fracture healing because of prominence (Zlowodzki et al., 2005). There is a risk of neurovascular damage with screw placement (Galley et al., 2009). Both of these risks might be reduced by anterior-inferior placement of the plate (Collinge et al., 2006,Kloen et al., 2002,Kloen et al., 2009) but the superior plate position offers a more secure fixation (Celestre et al., 2008,Iannotti et al., 2002,Robertson et al., 2009). The reported rate of infection in a large systematic review was 1%(Zlowodzki et al., 2005) but some reports were up to 7.8% (Bostman et al., 1997). Most of the implant related problems are now addressed with specific designed clavicular plates with angular stability. Plate osteosyntheses still remains the golden standard for osteosyntheses of fresh clavicular fractures (Kim and McKee, 2008) and is the most frequently used technique.

Percutaneous intramedullary osteosyntheses is another option for primary osteosyntheses of mid-shaft clavicular fractures. This technique has been described with different implants, varying from kirchner wires, different sorts of pins to elastic titanium nails, for this problem (Chu et al., 2002,Frigg et al., 2009,Grassi et al., 2001,Jubel et al., 2003,Ngarmukos et al., 1998,Smekal et al., 2009). The technique can be used antegrade or retrograde. An extra incision to facilitate fracture reduction and guidance of the pin through the fracture site is usually necessary. Because of the narrow medulla and the curvatures of the clavicle the challenge for the implant is to be flexible and small enough to be able to pass through the narrow medullary canal and to also be rigid enough to offer the stability needed for the clavicle. This kind of implants can help maintaining the alignment but offer no rotational stability and with comminuted fractures shortening of the clavicle can still occur. Advantages are the soft tissue friendly and less invasive procedure with theoretically little risk of damaging neurovascular structures. Disadvantages are higher reports of non-union (, 2004) and several reports about complications with these procedures such as failure of the implant, wound problems over the point of entry, temporary brachial plexus palsy and even implant migration in the direction of the great vessels (Frigg et al., 2009,Lyons and Rockwood, Jr., 1990,Nordback and Markkula, 1985,Ring and Holovacs, 2005,Strauss et al., 2007).

The cases in which primary osteosyntheses should be considered an optimal treatment is still under debate but displacement, shortening, comminution and fractures on the dominant arm have all proved to be factors predisposing for an unfavourable outcome after conservative treated mid-shaft clavicular fractures (Eskola et al., 1986,Hill et al., 1997,McKee et al., 2006,Nowak et al., 2004,Nowak et al., 2005). In the flow chart we listed the factors for making a treatment decision based on the currently available evidence (fig.2).

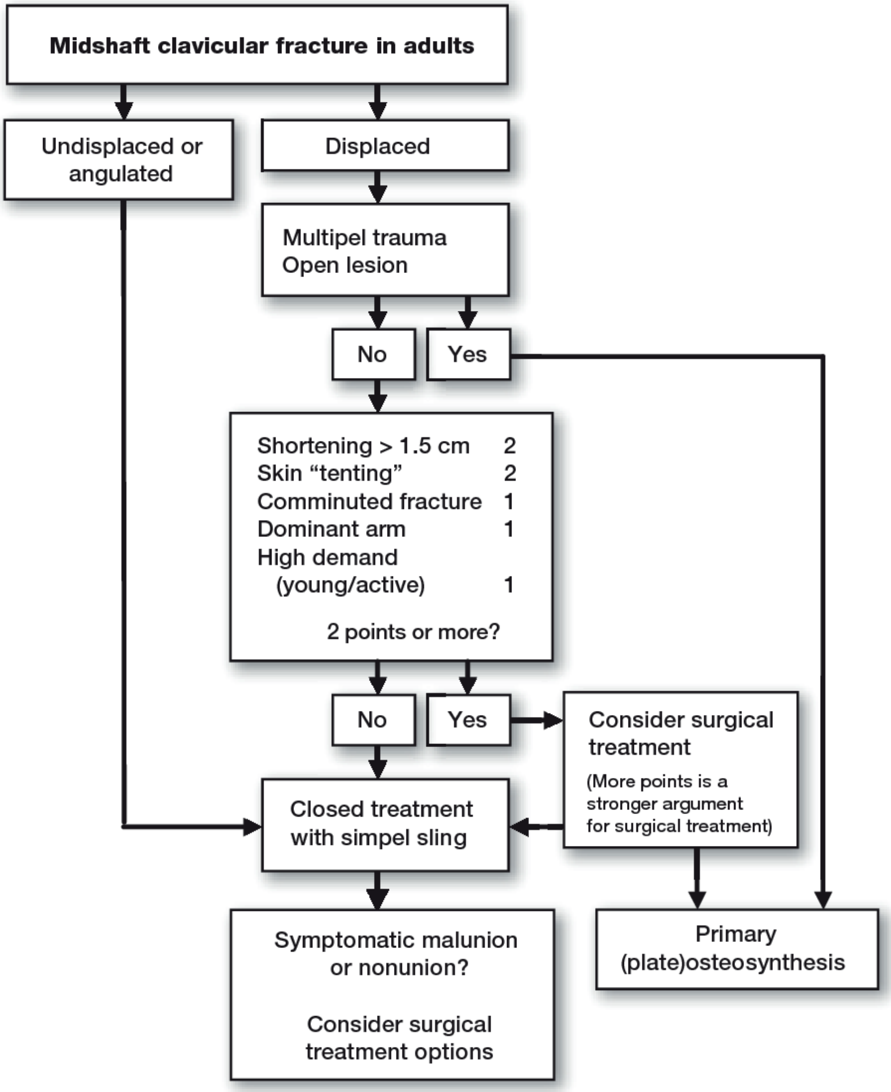

Figure 2. suggested flow chart for making treatment decisions

Symptoms of malunion after mid-shaft fracture and incidence of these symptoms

Early reports in the sixties by Neer (1960) and Rowe (1968) founded the basis for the concept that little problems are to be expected after conservative treatment of clavicular fractures with regard to non-union and functional problems. This was because the outcome was tested in terms of range of motion and fracture union on X-ray. Rowe stated: "Fortunately for man nature has endowed the clavicle with excellent reparative powers". This applies to fracture union and does unfortunately not apply to the restoration of length and rotational deformities of the clavicle after a fracture. There are also more recent studies that concur with the findings of Neer and Rowe (Nordqvist et al., 1997,Oroko et al., 1999). In the last decade a number of studies, using a patient based outcome score, have been published stating that a malunion with shortening after a mid-shaft clavicle fracture may lead to symptoms such as pain, loss of strength, rapid fatigability, paraesthesiae of the arm and hand, problems with sleeping on the back as well as cosmetic complaints (Hill et al., 1997,Ledger et al., 2005,McKee et al., 2006,Nowak et al., 2005,Rosenberg et al., 2007).

Complaints vary from mild to serious impairment in daily activities. Chan et al. (1999) reported atrophy of the trapezius muscle. Ledger et al (2005) showed that there was a loss of strength in patients with a shortening of the clavicle. He also noticed a reduced peak shoulder abduction velocity. Patients identified recreational activity as the area in which the functional loss was most evident. So, it seems that the functional problems patients experience are in the outer limits of the shoulder function. Reported incidence of unsatisfactory outcome after conservative treatment of a displaced mid-shaft clavicular fracture vary from 4.4% to 31% (Nowak et al., 2005,Lazarides and Zafiropoulos, 2006,Hill et al., 1997) but the definition of unsatisfactory outcome varies between the mentioned studies. Most authors have reported residual pain during activity or even in rest and loss of strength as main issues for an unsatisfactory outcome. Asking the opinion of the patient (for example: are you satisfied with the outcome?) is also used as an outcome factor in several studies. Unpublished data from our own studies showed 30% of a consecutive series of patients with a dislocated fracture had a DASH score of above 20. The altered view on clavicular malunion is because of several reasons: First there are better designed studies, without the inclusion of children, looking separately at specific problem groups within the Allman 1 type fractures (displaced fractures). Second there is an increased patient expectation on functional outcome after trauma and last but probably most important is that outcome after malunion is now analysed with a patient based outcome score rather than just radiological union and range of motion (Smekal et al., 2008,Kim and McKee, 2008). Many suggestions have been made as to what causes these symptoms. These can be divided in a number of categories:

Glenoid orientation / scapular winging: Because of the shortened lever arm of the shoulder girdle there is a change in orientation of the glenoid with winging of the scapula which leads to functional problems of the shoulder in overhead movements. The change in orientation of the glenoid might also result in increased shear forces across the glenohumeral joint (Ledger et al., 2005,Chan et al., 1999,Andermahr et al., 2006). The increased protraction and tilt of the scapula can result in pain when laying on the back.

Muscular. Shortening of the clavicle has a negative effect on muscle tendon tension and muscle balance leading to functional problems of the shoulder. This would lead to loss of strength and endurability which can be measured in patients with a short malunion (McKee et al., 2003,McKee et al., 2006,Ledger et al., 2005).

Neurovascular problems / thoracic outlet syndrome has been described after clavicular malunion, often associated with large callus formation. Patients complain of pain and rapid fatigability during overhead work (Chen and Liu, 2000,Connolly and Ganjianpour, 2002,Fujita et al., 2001,Onstenk et al., 2001).

AC / SC joint problems: The change in resting angle of the sc joint after malunion (Ledger et al., 2005) must result in a changed load of the ac and sc joint. Hill et al. (Hill et al., 1997) reported AC arthrosis seen in patients after follow up of malunited clavicular fractures.

It is likely that all of these explanations play a role in the problem. A decrease in length of the clavicle results in an alteration of the scapula position on the thoracic wall. Due to the ellipsoid shape of the thorax, changes in clavicular length result in non-linear changes in scapula position: each additional millimetre of shortening results in an exponential increase in scapula malposition. This can lead to all of the above-mentioned problems and shows that the amount of shortening must be a factor.

Treatment of symptomatic malunion after mid-shaft fracture

Conservative: to our knowledge no studies have been published about conservative treatment of a malunited mid-shaft clavicle fracture, but it seems logical to start with conservative measures before rendering to surgical options for a symptomatic malunion of a mid-shaft clavicular fracture. Conservative treatment options can by means of manual or physical therapy or medication. Pain medication can be used for a period of time but is not a descent option for long lasting pain or loss of function. Paracetamol or NSAID's should be considered. There is little place for the use of opioids in these sort of chronic pain problems.

Manual or physical therapy can be used to mobilize a stiff shoulder or regaining the lost strength by active and passive motion as well as specific muscle training. The result of trying to re-align the scapula by manipulation is most likely unsuccessful because the underlying structural problem remains. If pain medication or physical therapy does not give relieve or if the problems return after stopping of the analgesia or the physiotherapy surgical treatment should be considered.

Operative: Several reports about the operative treatment of malunited clavicular fractures have been published (Basamania C.J., 1999,Bosch et al., 1998,Chan et al., 1999,Hillen and Eygendaal, 2007,McKee et al., 2003,McKee et al., 2004,Rosenberg et al., 2007,Simpson and Jupiter, 1996), Though all of them are small series with low level of evidence, all of them show good results. The ways of expressing the results differed, but the two largest series expressed the results in terms of DASH score. The mean reported decrease was between 20 (McKee et al., 2003) and 33 (Hillen and Eygendaal, 2007). There was a large variance on the reported residual dysfunction. Most authors used a similar technique with or without a bone graft. It is useful to have a look at the original fracture X-ray to better understand the malunion. The technique described by Mc Kee et al (McKee et al., 2004) suggests an osteotomy through the original fracture plane. The patient is placed in a beach chair position under general anaesthesia; the arm does not need to be draped free. The iliac crest is draped free in case of the need for bone grafting is expected. An oblique incision along the superior border of the clavicle is made. When the skin and myofascial layers have been dissected the malunion can be visualized. The original fracture plane is usually identifiable because of the typical pattern of the fracture ends relative to each other. The osteotomy is performed through this plane; If the original fracture cannot be easily recognized an oblique sliding osteotomy can be performed. In both ends of the bone the medullary canal should be open to restore blood supply to the osteotomy site. The length and alignment are restored with the opposite side as a reference for length measurement. If the "old fracture ends" can be recognized these can also serve as a reference for restoring the length.

Now the ends are fixated by means of either a pelvic reconstruction plate or a precontoured clavicle plate and compression should be applied over the osteotomy. The plate is positioned most of the time on the postero-superior surface of the clavicle, especially pre contoured plates (Huang et al., 2007) but the antero-inferior surface can also be used (Collinge et al., 2006,Kloen et al., 2002,Kloen et al., 2009). The advantages reported of this method are less prominence of hardware and reduced risk of neurovascular damage because the screws are directed away from vulnerable structures. An intramedullary device for stabilisation has also been described (Chen and Liu, 2000,Basamania C.J., 1999) After stable fixation, the shoulder can be mobilized immediately but forces should be limited to prevent hardware failure. Little is known about the timing of treatment but correction osteotomy performed within 2 years after the fracture seemed to have better results than those performed a long time after fracture healing (Hillen and Eygendaal, 2007). The risk of complications must be considered. Apart from hardware irritation requiring plate removal, due to infection, failure of fixation, and non-union are the most frequent complications reported, with frequencies up to 20% (Table).

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Chapter 3

The effect of experimental shortening of the clavicle on shoulder kinematics

Hillen RJ, Burger BJ, Poll RG, van Dijk CN, Veeger DH. The effect of experimental shortening of the clavicle on shoulder kinematics. Clinical Biomechanics 2012;27(8):777-81.

Abstract

Introduction: An experimental cadaveric study was performed on five shoulders of three fresh frozen specimens. The specimen was fixed in an upright position that allowed free motion of the shoulder girdle. We measured position of the bony structures with an optotrak system (Northern Digital Inc.) in rest and during in a series of motions. Measurements were done with a normal clavicle and after shortening of the clavicle by 1.2, 2.4 and 3.6 cm. The shoulders were moved manually by one of the researchers. We examined for changes in resting position and during movement that resulted from the experimental shortening of the clavicle.

Results: In the resting position, winging of the scapula increased (on average protraction increased by 20° lateral rotation changed 12° and posterior tilt decreased by 7°) with resultant changes in the orientation of the glenoid, acromioclavicular and sternoclavicular joint and an altered position of the clavicle. Clavicle shortening affected sternoclavicular joint rotations but did not do so in the acromioclavicular joint. In arm elevation the offset in scapula orientation at resting position stayed relatively constant over the full range of motion but the amount of disposition is progressive in relation to the amount of shortening.

Conclusion: Shortening of the clavicle leads to significant changes in the shoulder girdle in resting position and in movement. We quantified these changes and discussed the clinical relevance.

Introduction

Clavicular fractures encompass 5-10% of all fractures (Khan et al., 2009,Robinson, 1998). Proximally 70% of the clavicular fractures are located in the mid-shaft of the clavicle (Khan et al., 2009,Robinson, 1998). Of these, in over 70% of cases dislocation is either present at initial presentation or is developed over time (Khan et al., 2009,Nordqvist et al., 1997,Robinson, 1998). If treated conservatively, this results in a malunion independent of the method of treatment. In the last decades there is discussion whether a clavicular malunion has any clinical relevance other than cosmetic (Allman, Jr., 1967). An association between clavicular malunion and loss of strength in the shoulder, rapid fatigability, pain, numbness and paraesthesia of the arm has been demonstrated by several authors (Eskola et al., 1986,Hill et al., 1997,Hillen and Eygendaal, 2007,Kibler and Sciascia, 2010,McKee et al., 2003,McKee et al., 2006), although Oroko et al. (Oroko et al., 1999) could not demonstrate such a relationship. It is unclear as to what causes these sequelae. Restoring the length of the clavicle has demonstrated to alleviate these symptoms (Hillen and Eygendaal, 2007,McKee et al., 2003,Allman, Jr., 1967,Bosch et al., 1998,Chan et al., 1999,Rosenberg et al., 2007). Because of the closed chain effect related to the thorax-scapula-clavicle complex (Veeger and van der Helm, 2007,Teubner et al., 1991), Shortening of the will cause changes in the shoulder girdle because of altered movement constraints. Ledger et al. (Ledger et al., 2005) showed that this will result in an increased upward sternoclavicular (SC) angulation by 10 degrees and an increased anterior scapular version (protraction) by 6° (avg shortening 21.4 mm with a range from 15.9 to 33.4 mm). Both effects are accompanied by a reduction in strength of the injured arm by more than 10% percent for extension, adduction and internal rotation. Andermahr et al. (Andermahr et al., 2006) showed that shortening of the clavicle causes a significant anteromediocaudal shift of the glenoid and they suggested this to be the cause of the sequelae. In Andermahr's study the scapula and clavicle were treated as a rigid body and therefore it is difficult to estimate if the observed changes of the glenoid position of this *in-vitro* study coincide with reality since AC-rotations are likely to occur *in-vivo*.

Malunion of the clavicle does not seem to affect the range of motion of the shoulder girdle in general (McKee et al., 2003,Canadian Orthopaedic Trauma Society, 2007). However, rotation of the clavicle has not been described other than in normal motion (Andermahr et al., 2006,Inman and Saunders, 1946,Ludewig et al., 2009), or related to shoulder dysfunction (Ludewig et al., 2009,McClure et al., 2006). For better understanding of the effect of shortening of the clavicle on (passive) kinematics of the shoulder joint we performed a cadaver study in which the effect of clavicular shortening on shoulder position in resting position and during motion motion was quantified. It was our hypothesis that due to the effect of clavicle length on the scapula position, clavicular shortening would lead to significantly different acromioclavicular (AC) and sternoclavicular (SC) resting angles and a change in both the sternoclavicular and acromioclavicular joint motions during arm elevation.

Methods and materials

Five shoulders from three fresh-frozen specimens (2 male, 1 female, mean age 78.3, SD 1.7) were selected for analysis. A cadaver was strapped into a custom-made frame in a vertical position. Straps were tied at the level C1-C2 of the cervical spine and the pelvis to allow free motion the upper torso. Cluster markers from the Optotrak system (Northern Digital Inc., Waterloo, Ontario, Canada) were inserted in the clavicle, the sternum, the humerus and the scapula by drilling a 1.6mm screw tip Kirchner wire in the bone. During a calibration trial, anatomical landmarks and segmental local coordinate systems were defined according to the International Society of Biomechanics standard as described by Wu et al. (fig 1) (Wu et al., 2005). The rotation centre of the glenohumeral joint was determined using a helical axis estimation procedure (Veeger, 2000).

In a series of motion trials, the upper arm was brought manually, supporting the elbow and forearm, in different positions (abduction, forward flexion, and scapular abduction or scaption, i.e. elevation in a plane rotated 30° from the frontal plane) by one of the researchers. The movement was limited at the moment when considerable resistance was felt by the researcher. This was presumed to represent a normal range of motion, possible under active conditions. All motions were repeated at least five times and the reproducibility of the range of motion was high (average standard deviation for peak elevation angles was 2.1°). The data were collected throughout the whole range of motion (sampling rate 50Hz). Subsequently, an osteotomy of the clavicle was performed and a fragment of 1.2 cm was resected and the ends of the osteotomy were brought together and fixated by means of a Peri-Loc locking clavicular plate (Smith&Nephew, Memphis, USA) resulting in a shortening of the clavicle of 1.2 cm. We chose to resect 1.2 cm because this length correlates with the distance between the screw holes in the plate we used. Again, the same measurements of movement were done. We collected

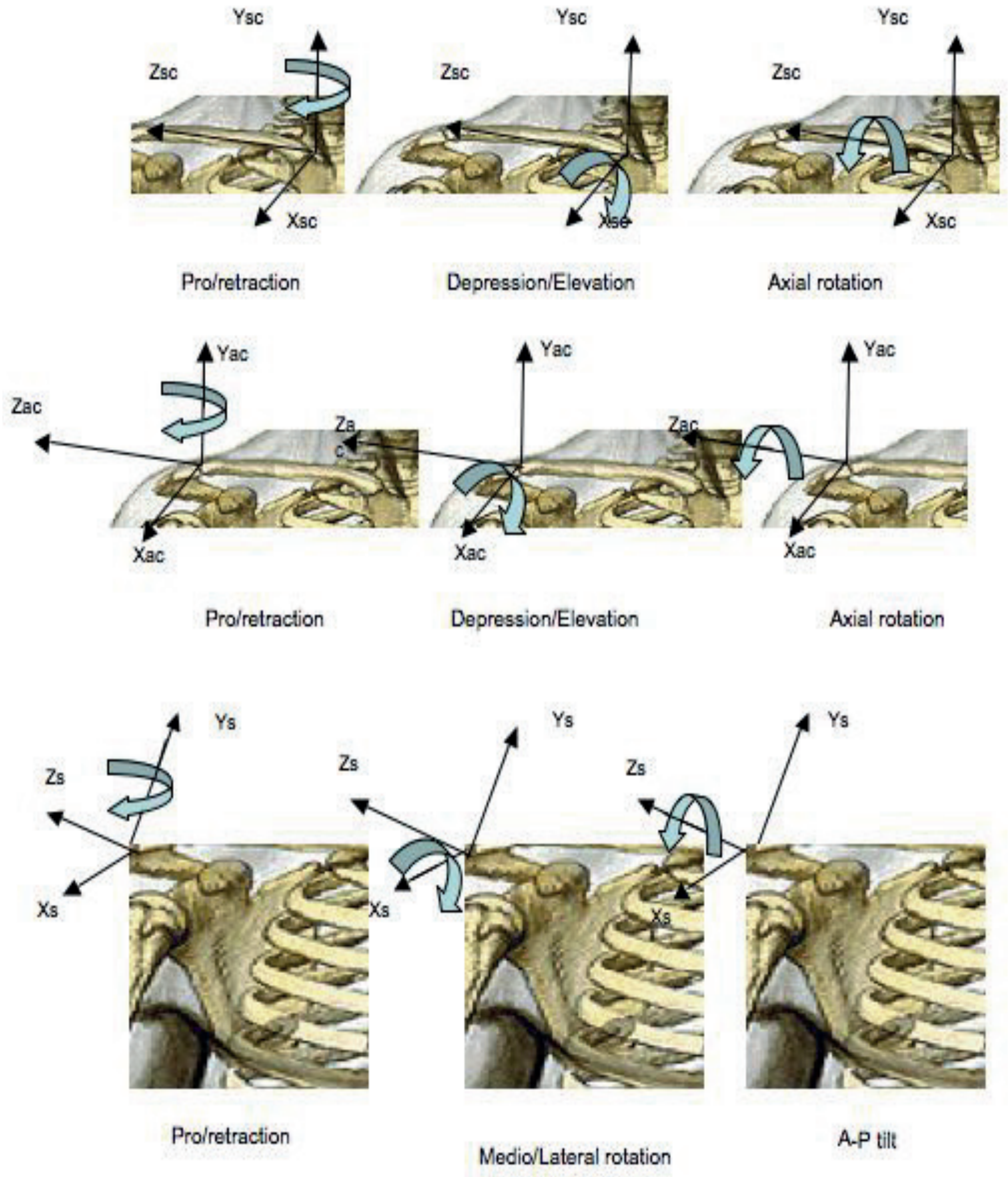


Figure 1. Euler angle definitions for the sternoclavicular and acromioclavicular joints and the scapulothoracic orientation.

data in 0, 1.2, 2.4 and 3.6 cm shortening of the clavicle. After the measurements the shoulders were dissected and we looked for signs of osteoarthritis or cuff tear. Three shoulders were found not suitable for analysis because of cuff tear arthropathy. All data were processed using technical coordinate systems, where anatomical orientations of these systems were defined using landmark coordinate systems following Wu et al. (Wu et al., 2005). Joint motions were subsequently calculated as the motion of the anatomical coordinate system relative to its proximal system (humerus, scapula, clavicle), or relative to the thorax coordinate system (humerus, scapula). We looked at 3 aspects of the shoulder girdle to examine these changes: SC joint -, AC joint - and scapulo-thoracic orientation. To compare the effect of shortening on the scapular resting position, the ST, AC and SC joint orientations were calculated at 30° thoracohumeral elevation and subsequently decomposed into Euler angles. According to the ISB proposal, the decomposition order for thoracohumeral and glenohumeral rotations were "plane of elevation" – "elevation" – "axial rotation". SC-, AC- and thoracoscapular rotations were decomposed in the order Y-X-Z, or "pro/retraction"– "latero-medial rotation" - "axial rotation" for AC and SC (fig 1). The thoracoscapular motion was defined as "pro/retraction" – "medio/lateral rotation" – "AP-tilt" as is shown in figure 1. From the full ranges of motion, the 30 – 120° range of motion was selected for the calculation of segment- and joint rotations. We defined 30 – 120° as range of motion to do our measurements to compensate for the differences within and between the specimens. The total angle of rotation from 30° to 120° was calculated using the helical axis method (Spoor and Veldpaus, 1980). This method defines the rotation from one condition to the other as the rotation around and translation over one uniquely defined axis, the helical axis.

The effects of clavicular shortening on joint orientation at 30° were evaluated using an ANOVA with orientation as within- and specimen as a between-subject factor. The effect of rotation from 30° to 120° was evaluated with an ANOVA with motion and shortening as within-subject factors and specimen as between-subject factor. Statistical analysis was done with SPSS version 17.

Results

For abduction the maximal (thoracohumeral) arm elevation angle was on average 129°±4°, with a contribution of 93°±5° for scapular lateral rotation. For scaption the mean TH elevation values were slightly higher: 132°±3 (Figure 2). There was no statistically significant effect of clavicular shortening on these measurements.

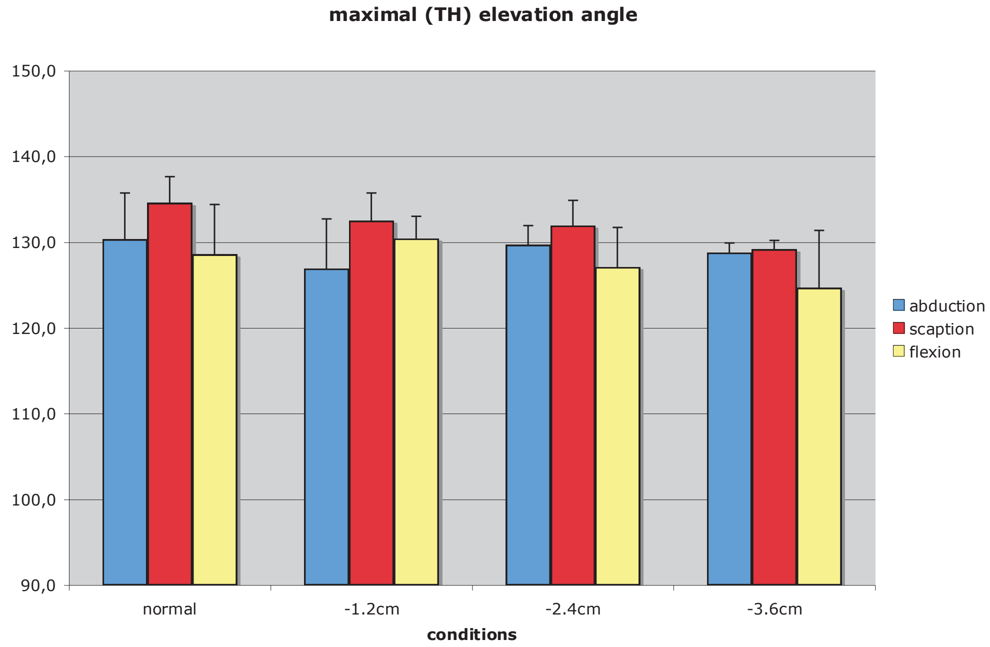


Figure 2. maximum thoracohumeral elevation angle for abduction, scaption and flexion in normal situation and in 1.2, 2.4, and 3.6 cm of shortening of the clavicle.

The orientation of the scapula relative to the thorax in 30° abduction changed significantly with clavicular shortening (fig 3). In the maximally shortened condition, the scapula was approximately 20° more protracted, 12° more latero-rotated and 7° more tilted. It was changed into a more "winging" position. The orientation of the clavicle in the SC joint was significantly changed for protraction and axial rotation, but not for elevation. The change in resting position was progressive with the amount of shortening. With shortening of the clavicle, the clavicle also gets significantly more retracted in the SC joint: on average 1.2° per 1.2 cm of shortening. The changes in the SC joint and the changed ST orientation combined resulted in substantial changes in the AC joint. The protraction significantly increased on average 7° per 1.2cm of shortening, leading to a total change of about 20°. Latero/medial rotations in the AC joint were relatively small, and amounted to approximately 2.5° for the largest shortening compared to normal. The axial rotation decreased approximately 9° (Table 1).

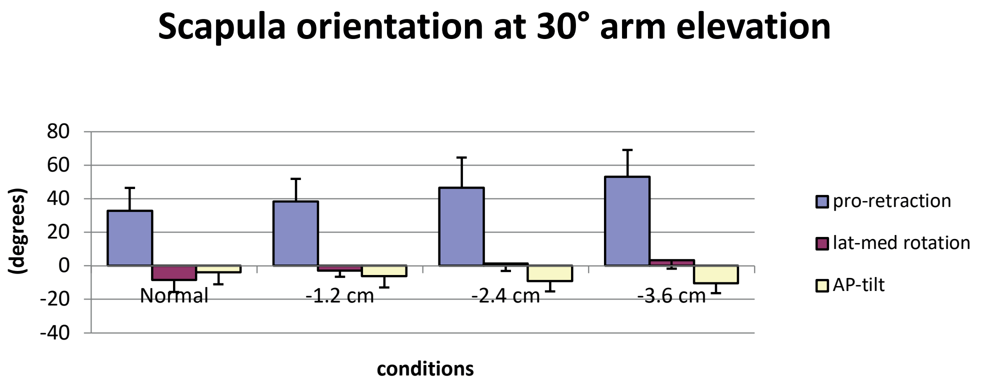


figure 3. scapula orientation in 30° abduction in normal situation and in 1.2, 2.4, and 3.6 cm of shortening of the clavicle.

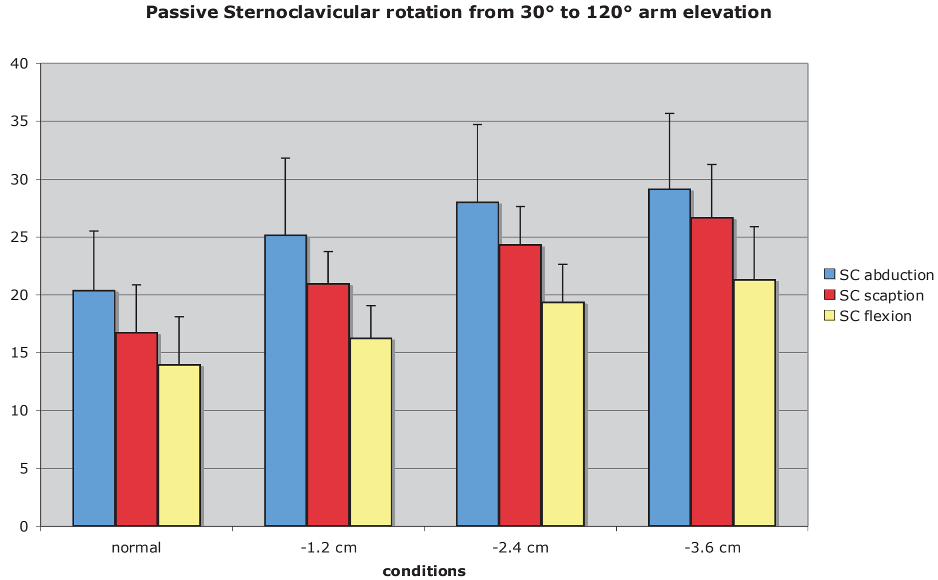
Table 1.

ANGLE (degrees)	Normal	1.2 cm shortening	2.4 cm shortening	3.6 cm shortening	
ST - Pro/Retraction	33.0±13.5	38.4±13.5	46.5±18.1	53.0±16.1	*
ST - Lateral/Medial rotation	-8.3±7.3	-2.7±3.7	1.4±4.4	3.4±5.0	*
ST - AP tilt	-3.8±7.2	-6.0±6.9	-9.0±6.2	-10.4±5.8	*
SC - Pro/Retraction	-42.4±12.0	-39.8±12.1	-38.1±12.0	-36.6±9.0	*
SC - Depression/Elevation	-13.9±7.1	-13.7±5.4	-12.7±4.1	-13.1±8.9	NS
SC - Axial rotation	1.9±1.0	0.6±1.9	-1.7±4.4	-1.8±3.2	*
AC - Pro/Retraction	74.9±5.3	79.3±5.2	88.3±4.2	93.4±4.8	*
AC - Lateral/Medial rotation	-0.1±2.7	0.2±4.6	2.2±7.6	2.4±7.2	*
AC - Axial rotation	12.0±3.4	9.2±3.5	6.1±3.0	2.9±6.1	*

Sternoclavicular (SC), acromioclavicular (AC) and scapulothoracic (ST) angles at 30° arm elevation for four different conditions: normal and a 1.2, 2.4, and 3.6 cm of shortening of the clavicle.

The offset in scapula orientation as found in 30° arm elevation stayed relatively constant over the full range of motion. As a result, AC joint rotations, expressed as the rotation around a helical axis, did not significantly change over the arm elevation range from 30° to 120° ($p=0.9$; Figure 4). The type of arm motion had no significant effect ($p=0.44$).

Total SC rotation for arm elevation from 30° to 120° arm elevation was increased from 17 to 26 after shortening ($p<0.001$). SC rotation was larger for abduction than for scaption and flexion ($p<0.01$).



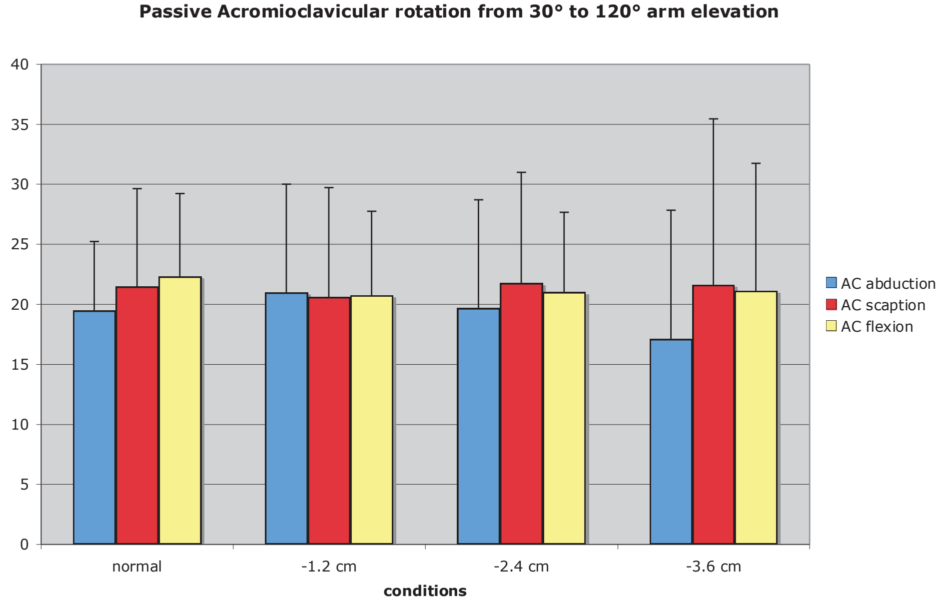


Figure 4. Rotation for abduction, scaption and forward flexion from 30° to 120° arm elevation in normal situation and in 1.2, 2.4, and 3.6 cm of shortening of the clavicle. Top: Sternoclavicular rotation. Bottom Acromioclavicular rotation.

Discussion

One of the drawbacks of this study is the limited number of shoulders that were measured and therefore the somewhat limited power of the statistical analysis. Four of the measured shoulders were from 2 specimens so the 5 shoulders were not independent. We corrected for this problem in our statistical analysis. The large standard deviations in scapulothoracic angles (see Table 1) were caused by the low number of specimen and the large inter-specimen differences. Given the measurement procedure this did, however, not affect the results for shortening since differences between shortening conditions were purely based on the changes in orientation of the technical marker clusters, which were screwed directly into the scapular spine with screw tip Kirchner wires, whereas offset differences were due to differences in scapular size, anatomical probing, or other systematic differences.

Another drawback was the measurement of passive motion. Our findings on passive motion in normal condition were well in line with *in-vivo* studies on active shoulder motion. These studies were performed in a similar method with sensors on the same bony structures as in our study (Teubner et al., 1991,McClure et al., 2006,Ludewig et al., 2009) so we expect that our findings after shortening might closely represent the changes that occur in active shoulder motion after shortening of the clavicle. The main effect of shortening of the clavicle was an offset of the normal position of the scapula, which resulted in a decreased tilt, an increased lateral rotation and an increased protraction. Because of the closed chain mechanism there were subsequent changes in orientation in the AC and SC joints. The peak passive Thoraco-Humeral elevation angles were quite similar to elevation angles reported in the literature for active elevation. Magermans et al (Magermans et al., 2005) reported a mean peak elevation angle for flexion and abduction of 131°. Although passive elevation does not necessarily reflect the active range of motion, in our specimen we did not find passive limitations at lower elevation angles that would prevent active elevation to occur. This also applies for the shortened condition. As a consequence, we concluded that clavicular shortening does not lead to limitation in arm elevation due to passive restraints, as already mentioned in previous studies (Canadian Orthopaedic Trauma Society, 2007,McKee et al., 2003). However shortening will also affect the muscular balance and might therefore still lead to a reduction in peak elevation due to a reduction in strength (Ledger et al., 2005). Shortening of the clavicle results in a reduced moment arm of the clavicular insertion of the pectoralis major muscle. The altered position of the scapula in relation to its surrounding structures results in secondary changes to all the surrounding muscles. The overall effect of shortening of the moment arm of the clavicular part of the pectoralis muscle, will effect forward flexion strength and abduction strength in higher abduction angles (Veeger and van der Helm, 2007). Kibler and Sciascia recently described the limitation in rotator cuff function because of the altered strut function of a shortened clavicle (Kibler and Sciascia, 2010). The loss of strength and endurability (McKee et al., 2003,McKee et al., 2006,Ledger et al., 2005,Hillen and Eygendaal, 2007) that is reported in patients with a mid-shaft malunion can be explained by these changes in position and resultant moment arm changes in the surrounding muscles. Quantification of the moment arm changes will require a further model-based study, which is the topic of the next chapter.

The altered scapula position that results from shortening of the clavicle leads to a changed resting position of the complete shoulder girdle. The position of the scapula is changed with a diminished tilt, increased lateral rotation and increased protraction. The diminished AP tilt and increased lateral rotation of the scapula result in a change of the position of the acromion in relation to the underlying humeral head and rotator cuff. The antero-lateral part of the acromion, which is thought to be responsible for impingement problems, is placed more anterior and more lateral. This results in a changed subacromial space. Whether this will result in impingement has not yet been clarified, but might likely occur.

The change of scapular resting position will result in an altered orientation of the glenoid. The change in orientation of the glenoid has been described earlier (Andermahr et al., 2006,Chan et al., 1999,Hillen et al., 2010,Ledger et al., 2005) and will to some extent influence the direction of the joint contact force. Assuming that in a balanced GH joint shear forces do not exist (Veeger and van der Helm, 2007), the altered orientation of the glenoid may result in a change in rotator cuff contribution to joint stability and ultimately a higher joint contact force. The different position of the scapula forced by the shorter clavicle does compare with complaints due to scapular dyskinesis, in which positional changes of the scapula can lead to impingement problems (Kibler and Sciascia, 2010).

The resting position and movement pattern of the clavicle is, because of the shortening, slightly changed in two ways: First by an increased protraction of the clavicle in resting position and a further increase in protraction in the end range of motion, especially in abduction. Secondly the clavicle is in resting position rotated anteriorly around its axis with an increase of this rotation in the end range of motion. All of the increased rotation takes place at the level of the SC joint. There is no increased rotation at the AC joint level. This might be explained by the stabilizing effect on the AC joint of the trapezoid en conoid ligament between the coracoid process and the lateral clavicle. The increased movements of the SC joint might lead to pain and degeneration of the SC joint.

Next to clinical evidence (Hillen et al., 2010) there is now also biomechanical evidence for the hypotheses that a short malunion of the clavicle can lead to shoulder dysfunction. A corrective osteotomy for symptomatic short malunion of the clavicle should be considered as an option for treatment. Whether shortened fractures should be treated primarily by an osteosyntheses is not clear yet and is still topic for further research (Stegeman et al., 2011).

Interpretation

Clavicle shortening leads to a clear difference in scapula resting position with a decreased tilt, an increased lateral rotation and increased protraction leading to a significant change in scapulothoracic and glenoid orientation. There is a progressive effect of shortening on the malposition of the scapula. The shortening also leads to a significant change in scapula position and orientation, which is maintained during the full abduction, scaption and forward flexion motion. The changed resting positions are reflected in the AC and SC joint orientations, but during abduction, scaption and forward flexion sternoclavicular rotation increases whereas acromioclavicular rotation does not.

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3

Chapter 4

The biomechanical effect of clavicular shortening on shoulder muscle function

a simulation study

Hillen R J, Bolsterlee B, Veeger D H. The biomechanical effect of clavicular shortening on shoulder muscle function, a simulation study. Clinical Biomechanics 2016; 37: 141-6.

Abstract

Background: Malunion of the clavicle with shortening after mid-shaft fractures can give rise to long-term residual complaints. The cause of these complaints is as yet unclear.

Methods: In this study we analysed data of an earlier experimental cadaveric study on changes of shoulder biomechanics with progressive shortening of the clavicle. The data was used in a musculoskeletal computer model to examine the effect of clavicle shortening on muscle function, expressed as maximal muscle moments for abduction and internal rotation.

Findings: Clavicle shortening results in changes of maximal muscle moments around the shoulder girdle. The mean values at 3.6 cm of shortening of maximal muscle moment changes are 16% decreased around the sternoclavicular joint decreased for both ab- and adduction, 37% increased around the acromioclavicular joint for adduction and 32% decrease for internal rotation around the glenohumeral joint in resting position.

Interpretation: Shortening of the clavicle affects muscle function in the shoulder in a computer model. This may explain for the residual complaints after short malunion with shortening.

Level of evidence: Basic Science Study. Biomechanics. Cadaveric data and computer model

Introduction

Mid-shaft clavicular fractures account for 5-10% of all fractures in humans (Khan et al., 2009,Robinson, 1998). In case of displaced clavicular fractures there is discussion about whether to treat these operatively or not (Jeray, 2007,Kim and McKee, 2008,McKee, 2010,Zlowodzki et al., 2005). Conservative treatment of displaced mid-shaft fractures usually results in shortening of the clavicle (Eskola et al., 1986,Hill et al., 1997,Hillen et al., 2010). Shortening was originally considered not to lead to serious limitations (Eskola et al., 1986,Nordqvist et al., 1998,Rowe, 1968), possibly based on outcome measures like fracture union and range of motion, but this is not consistent with patient reports: Around 30% of the patients with a shortened clavicle report residual complaints. Complaints include pain, weakness, rapid fatigability and numbness or paraesthesia of the arm and hand (Hillen et al., 2010). Why malunion with shortening gives rise to these complaints is as yet unclear. It is, however, clear that clavicular shortening leads to a change in scapular orientation, both in rest and in arm elevation. Shortening leads to a more "winged" position of the scapula. The change in the position of the center of glenohumeral rotation is larger than the amount of shortening (Hillen et al., 2012).

Shortening of the clavicle has a profound effect on scapular orientation and on the position of the glenohumeral joint (GH) (Hillen et al., 2012). It influences the geometry of the shoulder complex. The shortening of the clavicle after a mid-shaft fracture has been reported to be 1.2cm, with a range up to 3cm (Eskola et al., 1986,Hill et al., 1997,Nordqvist et al., 1997). This causes changes in anatomical geometry and in muscle moment arms of all muscles working directly or indirectly over the clavicle. The changes in geometry will also alter the length of muscles relative to their length-tension relationship curve. This effect will be most profound in muscles that have a clavicular origin distal from the fracture site. The GH medialization related to the shortening means that thoraco-humeral muscles are also affected. In a typical clavicular malunion with shortening the effect around adjacent joints will differ. The fracture is medial to the anterior deltoid origin, so the scapula-thoracic muscles shortening will only lead to changes in joint orientation and the effects on muscle strength might therefore be relatively small. This does not apply to the thoraco-humeral muscles pectoralis major and latissimus dorsi, whose insertions move considerably due to GH medialisation. It might be expected that these effects will be largest for arm abduction, as well as arm external – internal rotation. To our knowledge there is only one comparable computational study available at the moment. This study by Patel (Patel et al., 2012) also showed a decrease in maximal muscle moments for abduction and internal rotation but they only reported changes around GH. Patel et al. only shortened the clavicle by downsizing the clavicle size up to 20% which affects the anterior deltoid moment arm whereas this muscle's origin is usually lateral to the fracture site and not normally affected by post traumatic shortening. The scapula was medialized in the model without changing its orientation, which does not represent the actual scapula changes that must occur with clavicle shortening (Hillen et al., 2012,Matsumura et al., 2010) and is in fact impossible. Patel (Patel et al., 2012) showed a change in muscle potential around the GH after shortening. We felt that the muscles that are most likely to change are those crossing the fracture or those affected by the changed orientation of the scapula which would predominantly affect the sternoclavicular joint (SC). We therefore expect that the changes in muscle potential will be the largest around the SC.

Despite possible long-term adaptations of muscles to their new status after malunion, the effect of the geometrical changes on muscle potential can be visualized by the calculation of the maximal muscle moment (Ettema et al., 1998) around the sternoclavicular, acromioclavicular and glenohumeral joints. These differences indicate the immediate effect of such geometrical effects, including moment arm changes and changes in muscles' absolute and relative lengths. The changes might be related to the long-term complaints so often reported (Chan et al., 1999,Ledger et al., 2005,Patel et al., 2012). To explain these residual complaints, we would expect the moment arm for abduction and internal rotation to be reduced with shortening of the clavicle.

In this study we used the Delft Shoulder and Elbow model, a validated musculoskeletal model (Nikooyan et al., 2010,Nikooyan et al., 2011) to quantify the effect of clavicle shortening on maximal muscle moment for the GH, SC and acromioclavicular joint (AC). It was expected that changes in clavicle length would lead to a reduction in maximal muscle moment (MMM) around the SC and to a lesser extent the GH and AC.

Methods

Model input (kinematics)

Input data for the musculoskeletal model were derived from a cadaver study in which five shoulders from three fresh specimens (2 males aged 75 and

80,1 female aged 79) were measured (Hillen et al., 2012). To allow for motion recordings, the specimens' torsi were strapped into a special frame that kept the torso upright and allowed the arms and shoulders to move freely. For each specimen passive abduction kinematic data were collected in a process in which the experimenter moved the arm as if an active abduction was performed. This implied that the arm was raised, leaving the clavicle and scapula free to follow, to an elevation angle at which considerable resistance was felt. This final elevation angle was on average 129° (SD 4°) for abduction (Hillen et al., 2012). The motion was repeated three times and recorded with 3D optical analysis system (Optotrak, Northern Digital Inc.) using technical cluster frames that were screwed into thorax, humerus, scapula and clavicle on either side of the shortening. Local segment coordinate systems were defined based on anatomical landmark measurements. The motion recording protocol was also repeated after each of three clavicle osteotomies. In these three osteotomies, each time a fragment of 1.2 cm was resected and the ends of the osteotomy were brought together and fixated by means of a Peri-Loc locking clavicular plate (Smith&Nephew. Memphis. USA) resulting in a shortening of the clavicle of 1.2, 2.4 and 3.6 cm. The 1.2 cm steps were chosen because this was the distance between 2 screw holes on this type of plate and so preventing from having to drill many times over for each step in shortening and so destroying the specimen. All motion data were filtered using a second order low-pass digital Butterworth filter with cut-off frequency of 5Hz. Based on the impression that this would be the most illustrative, from all possible motion data, arm abduction was selected for analysis. To create an average motion input file, average joint angles were calculated for each motion file at 30° - 60° - 90° and 120° of arm abduction. These averages were calculated as all angles within approximately 5° arm elevation intervals. Subsequently, one input file was created, defined as the average over N=5 specimen.

Model

Motions were modelled with custom-modified versions of the Delft Shoulder and Elbow Model (DSEM). The DSEM is a finite element model that includes all bones, joints, muscles and most ligaments of the shoulder. Clavicular shortening was modelled by shortening the model's clavicle and recalculation of the shoulder geometry, following the method comparable to the method used previously for modelling of scapula neck fractures (Chadwick et al., 2004). Basically, insertions of the clavicular origins of deltoid, lateral part of trapezius, the conoid and trapezoid ligaments and the position of the GH were moved medially along the long axis of the clavicle with the same distances as the experimental shortening.

i.e. 1.2, 2.4 and 3.6 cm. The model's arm was moved together with the GH. This resulted in four model versions; one standard length clavicle version and three shortened clavicle versions.

Data processing

Input data for the model comprised clavicle orientation, scapulothoracic orientation and humerus orientation, calculated according to the ISB upper extremity proposal (Wu et al., 2005), measured separately for each (shortened) version and thus specific for that shortening condition, and reduced to the angle input belonging to 30° - 60° - 90° and 120° arm elevation at 0° plane of elevation, or arm abduction. Before starting the inverse-dynamics simulation, input kinematics were optimized to the model geometry to prevent the penetration of clavicle and scapula into the thorax, based on the standard optimization procedure as described by Bolsterlee et al (Bolsterlee et al., 2013).

Output of the inverse-dynamic analysis for this study were the maximal muscle moments for all muscles around the SC, AC and GH, calculated for 30° - 60° - 90° and 120° arm elevation at 0° plane of elevation, here now coined arm abduction, and expressed around the three thorax-defined main axes.

MMM (maximal muscle moments) were calculated as the cross product of moment arms and muscle lines of action, multiplied by their maximum force:

1. $$MMM = \sum_{i=1}^{n} \begin{pmatrix} r_{x,i} \\ r_{y,i} \\ r_{z,i} \end{pmatrix} \times \left\| \begin{matrix} l_{x,i} \\ l_{y,i} \\ l_{z,i} \end{matrix} \right\| * \ f_i(l_s) * PCSA_i * \sigma_{max} \, (N.m),$$

where r_i = the muscle's moment arm and l_i = muscle's line of action, $f_i(l_s)$ is the normalized muscle force-length relationship (Winters and Stark, 1985), $PCSA_i$ is the muscle's physiological cross-sectional area and σ_{max} is a maximum force of 100 N/cm^2. This implies that the MMM will be dependent on changes in moment arms as well as changes in the muscles' lengths.

Related to arm abduction, moments around the sagittal axis can be defined as abduction-adduction moments. Although MMM changes with clavicular shortening will occur in all three directions we chose to simplify interpretation of results by focusing on the main effects on potential muscle moments that were to be expected in abduction – abduction direction for arm elevation in the frontal plane. internal and external rotation maximal muscle moments were subsequently calculated for an arm position closest to the neutral arm position (30° arm abduction) and at 90° arm abduction. For these positions the internal and external rotation maximal muscle moments were defined as the components around the longitudinal axis (30° arm abduction) and around the frontal axis (90° arm abduction).

Results

After clavicular shortening and due to the accompanying clavicular rotation relative to the thorax, the GH rotation center moved more than the actual shortening distance (3.6 cm). The GH moved up to 40mm forward and 20mm medially. The shift on the vertical axis was smallest: about 9 mm downward for the 3.6cm shortened clavicle (Table 1). The change in position of the GH rotation center also changes the orientation (but not the position) of the humeral head relative to the glenoid. This change in orientation is due to both the shortening of the clavicle and the parabolic shape of the thorax, along which the scapula moves with shortening of the clavicle.

Table 1. Changes in orientation of the glenoid in three planes and the distance from the original position

	normal	1.2 cm shortening	2.4 cm shortening	3.6 cm shortening
X (forward)	75.9±31.9	12.7±6.4	26.4±6.7	40.5±9.1
Y (upward)	15.3±14.2	-6.2±1.9	-7.5±3.5	-8.9±3.5
Z (lateral)	150.0±10.4	-5.1±3.5	-11.8±7.8	-19.6±9.6
Distance (mm)	0	15.6±5.8	30.8±5.6	47.2±6.7

Ab- adduction moments: (figure 1 & table 2) The MMM generated around the sagittal axis or ab-adduction axis for the GH joint at 30, 60, 90 and 120 ° of arm elevation shows some reduction in the MMM that can be generated at 30 degrees of arm elevation can be seen (17% at 3.6 cm of shortening) but other than that there is little significant change. The MMM around the AC show that for the positive moment (upward) again there is little change but for the negative (downward) moment there is an increase for any amount of shortening of the clavicle length (mean value 37%). The most profound change for the negative MMM around the AC is seen at 3.6 cm shortening in 30 degrees of arm elevation (48%). For the MMM around the SC there is an overall reduction with shortening of the clavicle for the positive (upward average 17%) as well as the negative (downward average 16%) MMM.

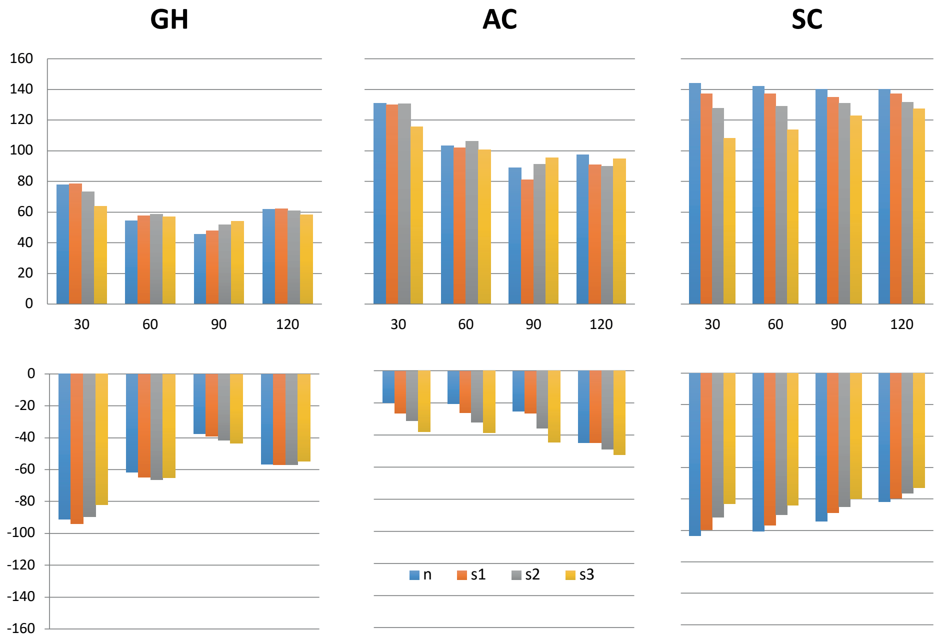

Figure 1. Maximal muscle moments (Nm) around the glenohumeral, acromioclavicular and the sternoclavicular joint for abduction (+) and adduction (-) in 30°, 60°, 90° and 120° of abduction in the normal situation (n) and with 1.2cm (s1), 2.4cm (s2) and 3.6cm (s3) shortening of the clavicle

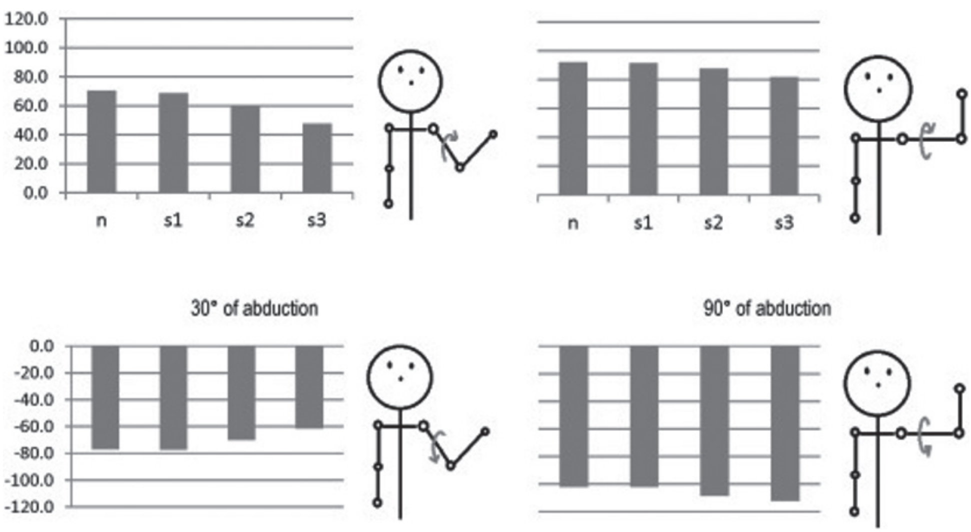

Figure 2. Maximal muscle moments (Nm) around the glenohumeral joint for external and internal rotation in 30° and 90° of abduction as showed by the illustration. Results in the normal situation (n) and with 1.2cm (s1), 2.4cm (s2) and 3.6cm (s3) shortening of the clavicle

Table 2. Maximal muscle moments(Nm) around the glenohumeral, acromioclavicular and the sternoclavicular joint for abduction and adduction in 30°, 60°, 90° and 120° of abduction

maximal muscle moments around the GH joint for abduction(+) and adduction(-)								
	n		**s1**		**s2**		**s3**	
30	78,0	-91,1	78,6	-94,1	73,4	-89,7	64,0	-82,1
60	54,3	-61,8	57,7	-64,7	58,7	-66,3	57,0	-65,0
90	45,6	-37,5	47,9	-39,0	51,9	-41,6	54,0	-43,4
120	61,9	-56,7	62,2	-56,9	61,0	-56,9	58,3	-54,7
avg	60,0	-61,8	61,6	-63,7	61,3	-63,6	58,3	-61,3
std	13,8	22,2	12,8	23,0	9,0	20,2	4,2	16,4
maximal muscle moments around the AC joint for abduction(+) and adduction(-)								
	n		**s1**		**s2**		**s3**	
30	130,9	-19,9	130,0	-26,6	130,5	-31,2	115,8	-38,1
60	103,2	-20,7	102,0	-26,2	106,3	-32,0	100,6	-38,7
90	89,0	-25,1	81,0	-26,4	91,1	-35,9	95,3	-44,7
120	97,5	-44,9	90,7	-45,0	90,0	-48,8	94,7	-52,3
avg	105,2	-27,6	100,9	-31,1	104,5	-37,0	101,6	-43,5
std	18,1	11,7	21,2	9,3	18,9	8,2	9,8	6,6
maximal muscle moments around the SC joint for abduction(+) and adduction(-)								
	n		**s1**		**s2**		**s3**	
30	144,0	-103,5	137,1	-99,7	127,8	-91,6	108,1	-82,9
60	142,0	-100,6	137,1	-96,8	129,0	-89,9	113,7	-84,0
90	140,0	-94,3	134,9	-88,7	130,9	-85,1	122,9	-80,0
120	140,0	-81,8	137,1	-79,6	131,6	-76,2	127,5	-72,7
avg	141,5	-95,0	136,6	-91,2	129,8	-85,7	118,1	-79,9
std	1,9	9,6	1,1	9,0	1,7	6,9	8,8	5,1

External- internal rotation: (figure 2 and table 3) MMM for external- and internal rotation in 30° (~ longitudinal axis) arm elevation and in 90° (sagittal axis) arm elevation were calculated from the model (table 4). In the resting position (30° abduction) the MMM decreases with shortening of the clavicle. The maximal internal rotation moment was reduced by 32% at 3.6 cm shortening, from 70.4 to 47.6 Nm. For external rotation the maximal moment decreased by 20% at 3.6 cm shortening, from 77.0 to 61.4 Nm. In 90° of abduction the decrease of maximal muscle moment for external rotation with shortening is much less than in the resting position (11% at 3.6 cm shortening, from 92.1 to 81.8 Nm) whereas there is an increase for the MMM for external rotation (9% at 3.6 cm shortening, 102.1 to 112.0 Nm.)

Table 3. Maximal moments(Nm) around the glenohumeral joint for external and internal rotation in 30° and 90° of abduction

max moments for internal rotation in 30° abduction			
n	**s1**	**s2**	**s3**
70,4	68,6	60,3	47,6

max moments for external rotation in 30° abduction			
n	**s1**	**s2**	**s3**
-77,0	-77,3	-70,0	-61,4

max moments for internal rotation in 90° abduction			
n	**s1**	**s2**	**s3**
92,1	91,4	87,7	81,8

max moments for external rotation in 90° abduction			
n	**s1**	**s2**	**s3**
-102,1	-102,0	-108,4	-112,0

Discussion

This study was based on our hypothesis that that shortening of the clavicle leads to reduced strength of the arm and shoulder girdle, as earlier reported by Patel (Patel et al., 2012), and thus be a possible factor for the development of long-term complaints. Differences compared to Patel et al. model were expected. This was due to our decision to use a modified scapular position and the analyses of the SC and AC. To analyze this, we used an average abduction motion, including the adaptation in scapular motion related to the clavicular shortening. We also calculated the maximal producible muscle moments for abduction and internal rotation. Results showed that MMM for internal rotation is reduced around the GH in the resting position as did the study by Patel but for abduction the MMM is reduced especially around the SC which differs from the findings in the study by Patel.

Maximal producible muscle moments (MMM) were used to report the effect of malunion. We chose MMM because this seems the most comprehensible indicator for how malunion effects muscle function. Moment arm changes are more difficult to interpret due to the three-dimensional nature of shoulder motion in which moments cannot be simplified as the effect of a moment arm in a single plane. In fact the maximal producible moment has been used previously for the same reasons (Veeger and van der Helm, 2007,Ettema et al., 1998) and has also been used in the form of the potential moment vector (Steenbrink et al., 2009). In addition, the MMM includes the effect of geometry changes on muscle lengths as it takes the force-length relationship into account (see Eq. 1). The maximum stress of 100N/cm^2 for muscles is an arbitrary value, commonly used in musculoskeletal modelling (Bolsterlee et al., 2015).

Our cadaveric derived data with passive scapular motion had similar findings to the data of several in vivo studies on active shoulder and scapular motion (Borstad and Ludewig, 2002,Ludewig et al., 2009,MacLean et al., 2014). Our findings are in line with the earlier studies for the reduced abduction and internal rotation strength (Ledger et al., 2005,Patel et al., 2012). We found a decrease in MMM especially around the SC for abduction and reduced MMM for internal rotation for the arm in resting position.

Although it is tempting to report the relative contribution of muscles to the abduction motion, we chose not to. It is difficult to study the change of the muscular strategy after a change in bony anatomy because the muscular strategy is dependent upon the model cost function (Praagman et al., 2006). Additional limitation of modeling the effect of geometrical changes on muscle function is that the change in MMM is under the assumption that muscle adaptations do not occur: that force-length relationships do not change and PCSA's do not do either. This might not be the case and so reported changes can (partially) be undone by adaptive processes. Changes in moment arm are however not subject to adaption and (in the case of a reduced maximal moment) muscles need to deliver extra force to perform the same task or motion as with a normal clavicle.

Shortening is often mentioned as being the crucial factor in residual complaints after conservative treatment of clavicle fractures (Eskola et al., 1986,Hill et al., 1997,Hillen et al., 2010,Lazarides and Zafiropoulos, 2006,Ledger et al., 2005,McKee et al., 2003,Nowak et al., 2004). We tried to define what the shortening of the clavicle changes in the biomechanics of the shoulder girdle. Changes in abduction strength are not likely to be found at the glenohumeral joint. The abduction muscles, the rotator cuff and deltoid, undergo very little change with shortening of the clavicle, in fact only due to a change in joint orientation. Our results show changes for abduction can best be found at the level of the SC because moment arms of muscles that cross that joint are most profoundly affected by clavicle shortening. The reduced abduction moment around the SC can be interpreted as diminished strength for positioning the scapula and clavicle complex. The increased MMM around the AC for the negative moment is also remarkable. The decrease around the SC and the increase around the AC will affect optimization strategies for the muscles in positioning the scapula-clavicle complex. Problems that patients report with a shortened clavicle (loss of strength in the shoulder, rapid fatigability, pain, numbness and paraestesiae of the arm and hand) can be explained by muscular problems. To our knowledge no information is available on the adaptation of muscles after traumatic or operative length changes. Adaptation of muscles to some extent to their new relative length is very likely.

Our findings differ from the earlier computational study on the same subject by Patel (Patel et al., 2012) as mentioned earlier. We found the changes brought on by clavicle shortening are to be found at the level of the AC and especially the SC and not so much the GH. The GH is only submitted to changes in orientation and not so much on moment arm length as is the case around the SC. Patel et al state that: "the clavicle acts as a linkage between the GH and the thorax, its shortening affects the length-tension relationship of the supporting musculature". This applies only to muscles that have attachments on either side of the mid-shaft clavicle fracture, at what site the shortening will take place, such as trapezius and pectoralis major and minor muscle. This does not apply to the rotator cuff muscles and the deltoid. The also applies for the MMM for the internal rotation of the arm: Our explanation is different. Patel

et al. explain the reduction by alteration of the anterior part of the deltoid. In a post-traumatic shortened clavicle there is however little or no change to this part of the muscle. More likely is that the reduced strength can be explained by changes in the pectoralis major and minor as these muscles do change with clavicle shortening. The change in shoulder geometrics after clavicle shortening and the resultant changes on muscle function we report may serve as an explanation for long term residual complaints reported after short malunion of the clavicle. The recent study by Stegeman (Stegeman et al., 2015) on scapular orientation with clavicular malunion showed similar results to our findings on the changes of the scapula.

To link our findings to the clinical issue of short malunion of the clavicle we still miss out on some important data. First it is unclear to what extend a change in MMM will result in fatigue or pain in the joint or what is a significant change in maximal muscle moment for the clinical situation. Second, we don't know to what extent the change in MMM can be compensated by training of the muscle.

Do changes in the load of the clavicle due to altered maximal muscle moments have an effect on the AC and SC? Looking at our data it can be expected that the change will have effects on these joints in the long run leading to degenerative changes and ultimately to osteoarthritis of either one of these joints. To our knowledge there is no literature in which AC or SC arthritis is related to an earlier sustained mid-shaft clavicle fracture. Incidence of degenerative joint disease for the AC and SC amongst people with a clavicle malunion compared to a control group can be a subject for future studies.

When should we operate on an acute displaced clavicle fracture? The current literature is not conclusive whether to favour surgical or conservative treatment (Kong et al., 2014, McKee, 2013, Robinson et al., 2013, Stegeman et al., 2015). Several arguments for surgical treatment can be found in the literature with patient (Age, arm dominance, occupation, activities) and fracture characteristics such as shortening, comminution, skin involvement (McKee, 2013,Robinson et al., 2013,Hillen et al., 2010). Our study proves that shortening will cause changes that lead to a less efficient shoulder function. Serious shortening and high demand on shoulder function are risk factors for developing sequelae after clavicle malunion. In case of an acute displace mid-shaft clavicle fracture with these characteristics surgical treatment should be discussed with the patient. The benefits of surgical treatment (reduced risk of non-union, no malunion and early mobilisation) should be mentioned as well as the risks (infection, implant related problems). The choice for surgical or conservative treatment can then be made with informed consent of the patient. The extra cost of surgical treatment are compensated by less pain and early return to work (Althausen et al., 2013).

How should we treat a symptomatic malunion? Based on the outcome of our study an improvement could be expected with training the trapezius muscle as this is the main muscle for creating the abduction moment around the SC. Also, improvement can be expected the training the serratus musculature for counteracting the protraction of the scapula and compensating for the loss of maximal muscle moment for adduction. Exercising of the pectoralis musculature can compensate for the reported loss of MMM for internal rotation around the GH.

There is also an option to restore the length of the clavicle when the conservative measures do not lead to significant improvement. A correction osteotomy restoring the length can be performed with good results (Hillen and Eygendaal, 2007,McKee et al., 2003,McKee et al., 2004,Rosenberg et al., 2007). This procedure is however more difficult than a primary osteosyntheses (McKee et al., 2004). It lacks the benefit of early mobilization after a fracture and introduces a risk of nonunion in a united fracture. The cost effectiveness is also less than in an acute procedure. Prevention of a symptomatic malunion might be preferred over treatment of a symptomatic malunion.

Conclusions

Shortening of the clavicle has little effect on GH and rotator cuff and deltoid muscle function for abduction but there is a significant decrease in the maximal muscle moment for internal rotation. Relevant changes for abduction are the altered resting position of the glenoid due to altered scapula position and the changes in MMM around the SC and AC. All these findings can explain the reported loss of strength and rapid fatigability that is reported after clavicle malunion.

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Chapter 5

Predictive factors for functional outcome after conservative treatment of mid-shaft clavicular fractures

Hockers N, Hillen R, Fransen B, Willems J, Hoozemans M, Burger B. Predictive Factors for Functional Outcome after Conservative Treatment of Mid-shaft Clavicular Fractures : A Retrospective Cohort Study. Clinical Research in Orthopedics 2017 (Technol Med). 1815;1:1–4.

Abstract

Background: The aim of this study was to identify factors based on radiological characteristics and nature of presenting history, that are predictive in functional outcome at two to nine years follow-up, in patients that were treated conservatively after a mid-shaft clavicle fracture.

Methods: We performed a retrospective cohort study of all patients that presented to the emergency department of Medisch Centrum Alkmaar in the Netherlands, between 2004 and 2006. Follow-up was performed at 2 to 3 years and at 7 to 9 years after injury. This resulted in a total amount of 48 and 31 included patients, respectively. The Disabilities of the Arm, Shoulder and Hand score (DASH score) was used to assess patient reported functional outcome. Statistical analyses were performed to detect correlations between characteristics of the patient or fracture and functional outcome.

Results: There was a significant decrease of 4.3 in DASH scores between the mid-term and long-term follow-up of patients with complete angulation of their fracture (p=0.041) and of 2.6 in DASH of patients who were not involved in a high energetic trauma (p=0.031).

Conclusion: With regard to completely angulated clavicular fractures and non-involvement in a HET, an increase of functional outcome is to be expected from mid- to long-term.

Keywords: Mid-shaft, Fracture, Clavicle, Outcome, Functionality

Background

A fracture of the clavicle is a common injury and makes up about 2.6%-4% of all fractures[1] and nearly 35% of all shoulder girdle injuries (Khan et al., 2009,Robinson, 1998). Over 75% of all clavicular fractures are fractures of the mid-shaft, Allman type 1 or Edinburgh type 2 fractures (Khan et al., 2009,Robinson, 1998). When displaced (Edinburgh type 2B fractures), these fractures tend to shorten the clavicle (Khan et al., 2009,Robinson, 1998).

Dislocation of the clavicle is caused by the combined effect of the sternocleidomastoid muscle pulling on the medial fragment superiorly and posteriorly, whilst the pectoralis major muscle, the deltoid muscle and gravity are pulling the lateral fragment inferiorly and anteriorly. The net effect of these forces is dislocation of the fracture ends relative to each other, with the lateral fragment lower than the medial fragment. Shortening, in turn, is caused by the force components of the pectoralis, the trapezoid and the latissimus dorsi muscles pulling the shoulder girdle medially. The shortening therefore is an ongoing process after a fracture (Hillen et al., 2010). This means that the amount of shortening on presentation can be less than after fracture (mal-)union(Hill et al., 1997,Plocher et al., 2011). Various techniques of closed reduction have proven to be unsuccessful in obtaining and maintaining alignment of the fracture (Khan et al., 2009,McKee et al., 2006,Robinson et al., 2004,Zlowodzki et al., 2005). Dislocation occurs in about 73% of mid-shaft clavicular fractures (Robinson, 1998) and the rate of non-union is found to be up to 15% (Hill et al., 1997,Khan et al., 2009,Robinson et al., 2004). Thus, the majority of conservatively treated mid-shaft fractures result in a malunion.

In the past, shortening has been considered to be of little or no clinical relevance (Neer II, 1984). However, published data in the last decades strongly suggest persistent residual symptoms associated with malunion of conservatively treated clavicular fractures (Eskola et al., 1986,Hill et al., 1997,Hillen and Eygendaal, 2007,Hillen et al., 2010,Khan et al., 2009,McKee et al., 2006,Postacchini et al., 2009,Zlowodzki et al., 2005). These persistent symptoms include pain, weakness, rapid fatigability, numbness or paraesthesia of the arm and hand as well as cosmetic complaints. The optimal treatment option for acute dislocated mid-shaft clavicular fractures as an isolated injury remains a matter of discussion (Canadian Orthopaedic Trauma Society, 2007,Khan et al., 2009,Zlowodzki et al., 2005). Recent studies show a trend towards operative intervention for dislocated mid-shaft clavicle fractures, with lower complication rates and increased functional outcome (Altamimi and McKee, 2008,Grassi et al., 2001). It remains unclear which factors influence outcome after conservative treatment. Therefore, these factors should be further recognised to aid in decision making for the choice of treatment.

To determine which patients should be selected for surgical treatment, identification of factors that can predict poor functional outcome upon initial presentation is vital. The aim of this study was, therefore, to identify factors based on radiological characteristics and nature of presenting history that are predictive in functional outcome at two to nine years follow-up, in patients that were treated conservatively after a mid-shaft clavicle fracture.

Methods

Study design and study population

We performed a retrospective cohort study of all patients that presented to the emergency department of Medisch Centrum Alkmaar in the Netherlands, between 2004 and 2006. Our inclusion criteria consisted of age over 18 years, a mid-shaft clavicle fracture as an isolated injury, no previous injury to the affected shoulder and a conservative treatment. This resulted in a total amount of 75 included patients.

Conservative treatment consisted of immobilization of the affected shoulder in a sling for a week, followed by mobilization as tolerated. Follow-up in the outpatient clinic was performed at one and six weeks after injury with a second X-ray at six weeks.

Procedure

The electronic filing system of the before mentioned hospital was used to select patients according to the inclusion criteria. After obtaining informed consent, a questionnaire was sent. Patients were contacted by phone when a response was lacking.

Functional outcome

Mid-term (MT) follow-up measurements were performed between 2 and 3 years after injury. All patients were sent a questionnaire that included the validated Dutch version of the Disabilities of the Arm, Shoulder and Hand score (DASH score). The DASH score is a self-reported questionnaire that includes 30 items on function of the upper limb. Scores range from 0 to 100, with a higher score indicating more impairment of daily function (Veehof et al., 2002). Long-term (LT) follow-up was performed between 7 and 9 years after injury by once again obtaining the DASH score. For the interpretation of the DASH score, to our knowledge, no official cut-off point for serious impairment has been described so far. The smallest clinically relevant change in DASH score is considered to be 16.3 points (van Kampen et al., 2013). We decided for the current study that a score above 20 represented serious impairment of the upper extremity in daily activities.

Predictive factor for high DASH scores

All X-rays made on presentation were rated by the second author (Hillen) with respect to dislocation and comminution. Complete dislocation was defined as no visual osseous contact between the medial and lateral fragment in one or both X-ray views. Angulation was defined as dislocation where there is still visual osseous contact between the medial and lateral fragment in both X-ray views. Comminution was defined as one or more loose fragments between the medial and lateral part of the clavicle in either direction on X-ray. In all cases a second X-ray was made after a minimum of 6 weeks to determine the presence of (mal) union of the fracture. No contralateral X-rays were available to adequately compare for shortening of the clavicle, and since shortening of the clavicula after injury is considered to be an ongoing process, we did not analyse shortening on presentation as a risk factor.

Besides complete dislocation, angulation and comminution, gender, whether or not the fracture occurred during a high energy trauma (HET) and if the fracture was in the patients' dominant arm, were assessed by questionnaire whether they were associated with functional outcome at mid- and long-term. Separate DASH scores were calculated with the patients grouped for these variables to examine whether there was a difference in the groups with or without that variable. To determine whether a combination of the chosen variables influenced the DASH scores a regression model analysis was also performed. When possible, odds ratios were calculated to determine if the chosen variables influenced the chance of achieving a DASH score of 20 and above.

Statistical analysis

Normality of the DASH scores was assessed using histograms, Q-Q plots, box-plots, Kolmogorov-Smirnov tests and z-values for skewness and kurtosis. Since the distribution of most scores was skewed, we performed non-parametric tests on all DASH scores. A p-value of <0.05 was considered significant.

We compared groups using a non-parametric test. Secondly, we created dichotomous variables of DASH outcome measurements with a low DASH score of <20 and a high DASH score of 20 or above. Then we performed univariate logistic regression analyses to determine differences between both groups in obtaining a high DASH score.

Furthermore, odds ratios and corresponding 95% confidence intervals (95% CI) were calculated in univariate analyses for all dichotomous predictor variables with two levels (gender, HET, dislocation (LT only), dominance and comminution). All statistical analyses were performed using SPSS Statistics, version 20 (IBM Corporation, Armonk, NY, USA).

Results

Participants and descriptive data

Patient characteristics are shown in table 1. At mid-term follow-up the questionnaire was returned by 52 patients (69%), and after file analysis 48 patients were included of whom all characteristics and a complete questionnaire were available. Of these patients, 31 (65%) returned the questionnaire for the long-term follow-up measurements.

Functional outcome

At mid-term follow-up the median DASH score was 4.5 and at long-term follow-up the median DASH score for all patients was 1.3 (of a maximum score of 100) (Table 1).

There was a significant decrease of 4.3 in DASH scores between the mid-term and long-term follow-up of patients with complete dislocation of their fracture and of 2.6 in DASH of patients who were not involved in a HET. There were no significant differences in DASH scores between mid-term and long-term follow-up for any of the other predictive variables.
Predictive factors for high DASH scores (≥20)

No significant differences in DASH scores were found at both follow-up measurements for any of the predictive factors (gender, type of trauma, dominance, dislocation, and comminution) when looking at the individual variables (Table 2).

Table 1. Patient Characteristics

	Mid-term follow-up N=48	Long-term follow-up N=31
Age at time of accident	40.9 (20-62)	44.3 (23-62)
Gender		
Female	11 (77%)	7 (77%)
Male	37 (23%)	24 (23%)
Dislocation		
Complete	35 (73%)	22 (71%)
Angulated	1 (2%)	0 (0%)
None	12 (25%)	9 (29%)
HET		
Yes	15 (31%)	8 (26%)
No	33 (69%)	23 (74%)
Dominant side		
Yes	40 (83%)	26 (84%)
No	8 (17%)	5 (16%)
Comminution		
Yes	21 (44%)	13 (42%)
No	27 (56%)	18 (58%)

Data in Mean (range) or Number (percentage); HET = High Energy Trauma

Table 2. DASH scores

	Mid-term follow-up			Long-term follow-up			MT versus LT
DASH	**Median (IQR)**	**Range**	***p*-value**	**Median (IQR)**	**Range**	***p*-value**	**p-value**
All patients	4.5 (14.9)	0-61.8	*0,139*	1,3 (6.7)	0-50	*0,530*	*0,101*
Gender							
Female	11,8 (21,1)	0-31,6		2,6 (15,8)	0-23,7		*0,345*
Male	3,9 (14,7)	0-61,8		0,7 (3,9)	0-50,0		*0,187*
Dislocation			*0,455*			*0,746*	
Complete	5,0 (21,7)	0-61,8		0,7 (6,9)	0-50		*0,041*
Angulated	-	-		-			
None	1,8 (14,1)	0-15		2,6 (9,0)	0-42,1		*0,917*
HET			*0,521*			*0,943*	
Yes	6,6 (12,7)	0-34,2		1,3 (9,5)	0-42,1		*0,799*
No	3,9 (16.1)	0-61,8		1,3 (6,7)	0-50		*0,031*
Dominant side			*0,193*			*0,568*	
Yes	5,3 (19,1)	0-61,8		1,7 (7,8)	0-50		*0,098*
No	2,6 (9,9)	0-13,2		0,0 (21,7)	0-42,1		*0,498*
Comminution			*0,720*			*0,718*	
Yes	3,9 (19.4)	0-36,8		0,0 (9,9)	0-23,7		*0,721*
No	5,3 (14,5)	0-61,8		1,5 (7,8)	0-50		*0,136*

IQR = interquartile range; HET = High Energy Trauma

The univariate logistic regression analysis showed no significant associations between the predictive factors and having a DASH score of ≥20 at mid- or long-term follow-up. The odds ratios for achieving a DASH score of 20 or above are shown in Table 3.

Table 3. Odds Ratios for having a score ≥20

	Mid-term		Long-term	
DASH	**OR**	**95% CI**	**OR**	**95% CI**
Gender (Female/Male)	1.9	0.4 – 9.5	1.2	0.1 – 13.4
Dislocation (Complete or angulated/None)	-	-	1.3	0.1 – 14.1
HET (Yes/No)	1.1	0.2 – 5.3	1.0	0.1 – 10.7
Dominant side (Yes/No)	-	-	0.5	0.0 – 6.4
Comminution (Yes/No)	1.8	0.4 – 7.7	1.5	0.2 – 11.9

Discussion

The aim of this study was to identify factors based on radiological characteristics and nature of presenting history, that are predictive in functional outcome at two to nine years follow-up. We performed a retrospective cohort analysis of 48 patients who were treated conservatively for a mid-shaft clavicle fracture. The results of this study indicate a significant improvement from mid-term to long-term in functional outcome in patients presenting with a completely dislocated mid-shaft fracture of the clavicle. Secondly, a significant difference in functional outcome was shown from mid- to long-term follow-up for patients who were not involved in a HET.

In current literature no differentiation has been made in functional outcome between mid- and long-term results. Our study shows a significant improvement in functionality for patients presenting with a completely dislocated fracture and for patients who were not involved in a HET. However, in the final follow-up these findings were not significantly different in DASH scores from patients with a complete dislocation or patients who were not involved in a HET respectively.

Given our results, the question rises what caused the registered increase in functionality for the before mentioned groups between mid- and long-term assessment. Since complete (mal)union and healing of the bone has been achieved before mid-term follow-up, an explanation might be found in coping with and adjusting lifestyle to the affected shoulder, but also muscle training. This might result in an increase of reported functionality even after mid-term follow-up.

A strength of this study is that we included two separate follow-up measurements, with a minimum of four years in between assessments. We also included most factors that are thought to influence outcome after a clavicle fracture in our analysis. A weakness of this study lies in the interpretation of dislocation on X-rays by a single author, because of a possible inter-observer variability. A second weakness, the absence of an adequate analysis on the effect of shortening, has been discussed. Thirdly, no data was available in particular of the degree of involvement in sports or overhead work.

Conclusion

This paper sheds some light with respect to decision making in the treatment of mid-shaft clavicular fractures. With regard to completely dislocated fractures and non-involvement in a HET, an increase of functional outcome is to be expected. It is of the utmost importance that for each patient individually, the most suitable treatment is applied. Our findings could aid in managing patient expectations with regard to functionality.

Declarations

List of abbreviations

MT	mid-term
DASH score	Disabilities of the Arm, Shoulder and Hand score
LT	long-term
HET	high energy trauma

Ethics, consent and permissions

Written consent was obtained from each participant

Conflict of Interest Statement

None of the authors declared any conflict of interest.

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5

Chapter 6

Long-term follow-up of conservatively treated mid-shaft clavicular fractures on functional outcome

6

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Abstract

Background: The aim of this study was to examine the long-term effect of shortening after a mid-shaft clavicular fracture on strength deficiency in the shoulder.

Method: This study included 18 participants (14 males, 4 females) with a conservatively treated mid-shaft clavicular fracture. Mean age was 52.2 ± 13.8 years, range 32 – 76 years). The mean follow-up time was 13.5 ± 0.4 years. Participants filled in a QUICKDASH questionnaire and both clavicle lengths were measured using a caliper. The isometric strengths in internal rotation, external rotation and abduction of both arms were measured with a handheld dynamometer.

Results: Average shortening of the clavicle in this group was 1.09 cm (SD 0.53). Nearly all strength measurements showed no significant difference between the shortened and the unaffected side. Multiple regression revealed a small (3N per mm length difference) but statistically significant relationship on external rotation between the relative extent of shortening of the clavicle, dominant side of the fracture and the isometric force difference between the unaffected and affected arm, $F(2,15) = 5.746$, $p < .05$, adj. $R^2 = .358$. Over 14 years there was a reduction in mean DASH-score of 4.4 (8.8 ± 12.3; current DASH = 4.4 ± 7.7)

In this group, long term effects of clavicular shortening were small. Based on these results we conclude that on the long-term clavicular shortening will not result in significant strength loss.

Introduction

Clavicular fractures are common as they account for 2.6% - 10% of all fractures (Nordqvist and Petersson 1994, Robinson 1998, Postacchini et al. 2002). Between 69% and 82% of these occur in the mid-shaft of the clavicle (Rowe 1968, Robinson 1998). Traditionally, the large majority of those mid-shaft fractures were treated conservatively, based on excellent results in reports of Neer and Rowe which showed a low (<1%) nonunion rate (Neer 1960, Rowe 1968). In case of displaced mid-shaft clavicular fractures treated conservatively this results in some degree of shortening. The displacement is caused by the sternocleidomastoid muscle elevating the medial fragment and pulling it posteriorly whereas the lateral fragment is displaced downwards and anteriorly under influence of the deltoid muscle, the pectoralis major muscle and gravity. Subsequently, the shoulder girdle is pulled medially by the pectoralis-, latissimus dorsi- and trapezius muscles, causing the actual shortening of the clavicle (Khan et al. 2009, Hillen et al. 2010). Conservative treatment of displaced mid-shaft clavicle fractures and the shortening and deformity that comes with it was considered not to give rise to serious problems. However, more recent studies have shown that the nonunion rate of conservatively treated displaced mid-shaft clavicular fractures is higher than was previously thought and that shortening of the clavicle is associated with poorer functional outcome (Eskola et al. 1986, Hill et al. 1997). Moreover, patient reports have shown complaints including pain, rapid fatigability, weakness, numbness of the arm or hand and difficulties with activities of daily living (Ledger et al., Eskola et al. 1986, Hill et al. 1997, Hillen et al. 2010).

Shortening of the clavicle will cause profound anatomical changes in the shoulder girdle biomechanics (Hillen et al. 2012). These changes will mechanically cause changes in maximal strength of the shoulder. This has been tested in several clinical studies with different outcomes (Ledger et al., McKee et al. 2006, Schulz et al. 2013, Su et al. 2016, Parry et al. 2017).

Little information is available about the effect of clavicular shortening on the long term. Possibly the effect of clavicular shortening on the length-tension relationship and the mechanical efficiency of the muscles will continue to decrease over the years. Furthermore, muscles can possibly adapt to their new condition after clavicular malunion. Given the information that training can induce an increase in physiological cross-sectional area of a muscle, training can possibly compensate for the loss in maximal muscle moments due to clavicular shortening and the resulting changes in muscle moment arms (Hillen et al. 2016). The purpose of this study is to determine whether there are differences in strength between the affected and unaffected arm in patients with post traumatic shortening after unilateral conservatively treated mid-shaft clavicular fracture with a long follow up of more than 13 years after injury. We also want to determine what the relationship is between the degree of clavicle shortening and the effect on muscle strength in the shoulder. Furthermore, we want to determine if there has been a change in functional ability of the shoulder, arm and hand over the years after a conservatively treated clavicular fracture. We hypothesized that the larger the extent of shortening of the clavicle, the larger will be the strength difference between affected and unaffected arm in isometric abduction, internal and external rotation strength tests.

Method

Patient in-/exclusion

We contacted participants of a previous study on outcome of conservatively treated mid-shaft clavicular fracture (Hockers et al. 2017). From this group we managed to include 18 participants. 23 of the original 41 could not be included. 2 of these were excluded due to a secondary surgical treatment, 2 others sustained a clavicle fracture on the contralateral side which could therefore no longer serve as a reference point. 11 participants could not be reached to participate in the current study, and 8 participants refused to participate. The characteristics of the participants that dropped out (based on the original DASH scores) did not significantly differ from the group that did participate. Selected participants were healthy, did not suffer any other injury of the upper extremity in the past years next to the clavicular fracture and were able to perform maximal strength measurements with their arms.

Test and measures

Permission for this study was obtained from the local Ethical committee. The setting of this study was at the participants' homes. Prior to the tests, participants were informed on the aims and risks of the study and signed an informed consent. Participants filled out the abbreviated version of the Disability of Arm, Shoulder and Hand (QUICK-DASH) questionnaire (Hudak et al. 1996). The outcome is a DASH score on a scale from 0 – 100, where 0 indicates "no disability". The DASH scores of the participants were compared to their DASH scores of 13 years ago to determine whether there has been any change in functional ability of the upper extremity over time. The length of the clavicle on both sides was measured with a caliper. The subject was asked to partially expose the upper part body and the clavicle was marked on the AC and SC joint. The length of both clavicles was measured three times at each side. Participants were asked for their weight and height to determine Body Mass Index.

Isometric strength testing

The isometric strengths of the participants' arms were measured using a MicroFET2 handheld dynamometer (Hoggan Health Industries Inc., UT, USA). The isometric strength was measured for the abduction, internal rotation and external rotation musculature of both shoulders. For strength testing we used the "make test" in which the tester holds the handheld dynamometer statically whereas the participant gradually upregulates its force to maximum and holds it for 4-5 seconds (Stratford and Balsor 1994). For isometric shoulder strength measurement, the participant was standing upright in a stable relaxed position. If a participant was not standing stable enough he/she was allowed to hold a chair or table with the non-tested arm. The abduction strength was measured with the shoulder 90 degrees abducted, elbow was flexed 90 degrees and the forearm pronated. The handheld dynamometer was placed just proximal of the lateral epicondyle and examiner was standing behind the participant. The participant was asked to perform a shoulder abduction movement with maximal effort while the examiner kept the dynamometer in place by matching the force exerted by the participant, as described by Rieman (Riemann et al. 2010). The internal and external rotation strength was measured with the shoulder at 0 degrees abduction, elbow flexed 90 degrees and the forearm in neutral position. For the isometric internal rotation strength measurement, the handheld dynamometer was placed just proximal of the ulnar styloid process at the volar side of the wrist with examiner standing in front of the participant. The participant was asked to perform a maximal force shoulder internal rotation movement while the examiner matched the participant's force. For the measurement of the shoulder external rotation strength the handheld dynamometer was placed just proximal of the ulnar styloid process, on the dorsal side of the wrist. Thereafter the participant was asked to perform a shoulder external rotation movement with maximal force while the examiner kept the dynamometer statically. The muscle strength test was repeated 2 times for each motion and for both arms. Between each repetition there was a period of 10 seconds rest and between each motion (abduction, internal or external rotation) was a period of 30 seconds rest. The peak force after each repetition was used for further analysis. The order of which side or which motion was measured, was randomized. The exerted forces were blinded for the participant to prevent a possible bias effect.

Statistical analysis

Means and standard deviations were calculated for all participants on dependent variables. The DASH score was calculated from the filled in questionnaire. Isometric strength values are in Newton (N). Forward stepwise multiple regression analyses were run to determine a relationship between the difference in isometric strength of the unaffected relative to the affected side with age, gender, magnitude of shortening, whether the fracture was on the dominant side and DASH score as dependent variables.

T-tests were run to determine any statistically significant differences between the means in isometric strength of the unaffected and affected arms and between the means in DASH scores of 14 years ago and current DASH score. All statistical analyses were performed using SPSS version 24 (IBM Corp, Armonk, NY, USA). The α-level was set on .05 for all analyses.

Results

18 Subjects (14 male, 4 female) with a conservatively treated mid-shaft clavicular fracture participated (mean age 52.2 ± 13.8 years, range 32 – 76 years). The mean time from injury to participation in this study was 13.5 ± 0.4 years. There were 10 clavicular fractures on the right side and 8 on the left side. Twelve clavicular fractures (66%) were on the dominant side. The mean shortening relative to the contralateral side, measured in vivo with a caliper, was 1.09 ± 0.53 cm, range 0.20 – 2.70 cm (see Table 1).

The mean DASH score was 4.4 ± 7.7, range 0 – 30. For 16 participants there was a DASH score available from a QUICKDASH obtained in 2006. The mean DASH score of that questionnaire was 8.8 ± 12.3, range 0 – 41. Because both QUICKDASH score variables were not normally distributed a related samples Wilcoxon Signed Rank Test was used to compare the means of both variables which turned out not to differ significantly (p = 0.20).

No significant differences in mean maximal isometric force levels between affected and unaffected side were found (Figure 1). Figure 2 depicts the difference in isometric strength of the affected side relative to the unaffected side. Multiple regression analysis indicated that only for external rotation the relationship of strength reduction and clavicular shortening reached significance (D = 2,0521x - 21,142*, r = 0.477, p=0.045).

The multiple regression model with the independent variables magnitude of shortening and whether the fracture was on the dominant side statistically significantly predicted the isometric force difference of external rotation between the unaffected and affected arm:

Table 1.

Overview of participant characteristics

Participant	Gender	Age (in years)	Clavicle Shortening (in cm)	Dominant arm affected	BMI	QUICK-DASH Score 2005	QUICK-DASH Score 2018
1	Male	33	1.1	Yes	26.60	-	2
2	Male	69	1.4	No	24.59	0	2
3	Male	54	0.3	Yes	29.86	0	0
4	Male	75	0.8	No	22.86	0	5
5	Male	68	0.7	No	24.51	0	2
6	Female	38	1.2	Yes	22.86	7	0
7	Male	69	0.2	Yes	28.27	2	2
8	Male	49	2.1	No	25.54	14	16
9	Male	32	1.8	Yes	21.26	2	0
10	Male	49	1.6	Yes	22.84	0	0
11	Male	45	2.7	Yes	26.32	2	0
12	Male	53	0.9	No	22.13	16	2
13	Female	52	0.6	Yes	22.15	0	0
14	Male	37	1.2	Yes	25.13	41	30
15	Male	47	1.1	Yes	24.15	-	0
16	Male	33	1.2	Yes	21.74	25	2
17	Male	73	1.8	No	26.26	2	9
18	Female	55	1.3	Yes	21.77	30	0
Range		32 – 75	0.2 – 2.7		21.26 – 29.86	0 – 40.9	0 – 30
Mean		52.24	1.09		24.4	8.8	4.4[a]

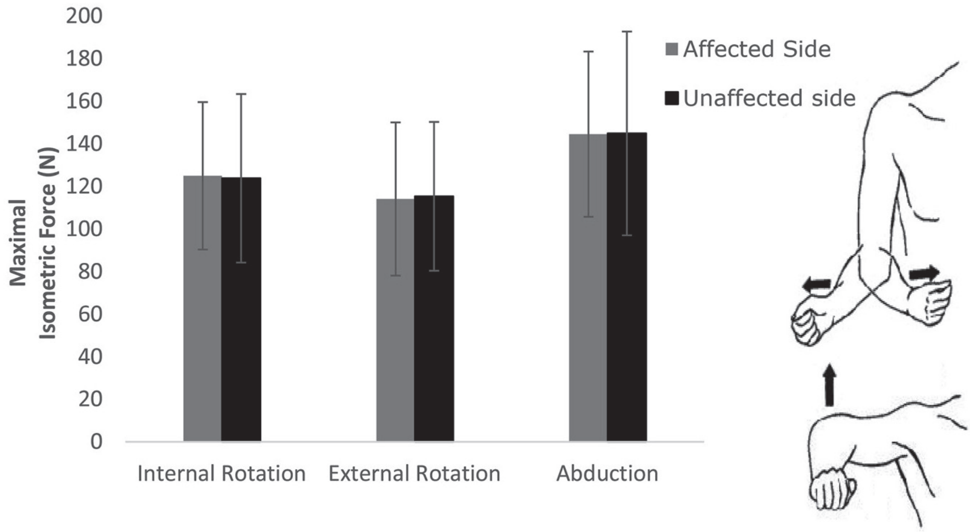

Fig. 1. Mean maximal isometric force (in Newton, N) of the affected and unaffected side on internal rotation, external rotation and abduction. The shoulder was abducted 0° for internal and external rotation and abducted 90° for abduction, as shown by the illustration. Error bars denote 1 standard deviation around the mean.

D = -49.222 + 3.098 (shortening) + 24.980 (affected on dominant side), where shortening is measured in millimeters and affected on dominant side is coded as 0 = no, 1 = yes. $F(2,15) = 5.746$, $p < .05$, adj. $R^2 = .358$. Both variables added statistically significant to the model, $p < .05$. (Table 2).

The relationship between the DASH score and clavicular shortening indicated a small but significant relationship between DASH and clavicular length reduction (figure 3). When looking at the strength loss, the predicted isometric force difference between unaffected and affected side for external rotation is equal to -4.780 + 1.270 (DASH), where DASH is the participant's DASH score (table 3). Analyses on abduction or internal rotation strength loss did not reach significance.

Discussion

The aim of this study was to determine if there are differences in strength between the affected and unaffected arm in patients with a unilateral conservatively treated mid-shaft clavicular fracture, with a long follow up (>13 years) after the fracture. Strength measurements were performed on shoulder internal rotation (shoulder 0° abducted, elbow 90° flexed), external rotation (shoulder

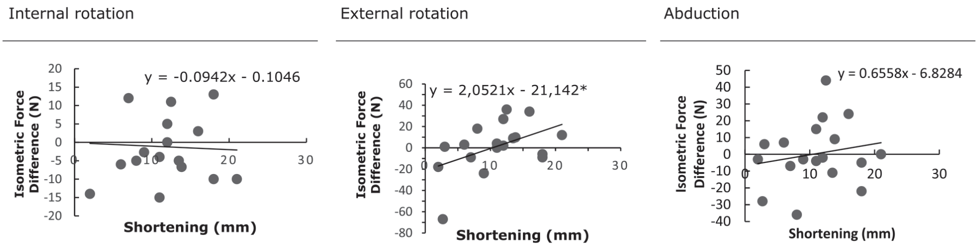

Fig. 2. Difference in maximal isometric force (in Newton, N) for the three strength tests of the affected side relative to the unaffected side, plotted against relative clavicle shortening (in millimeters).

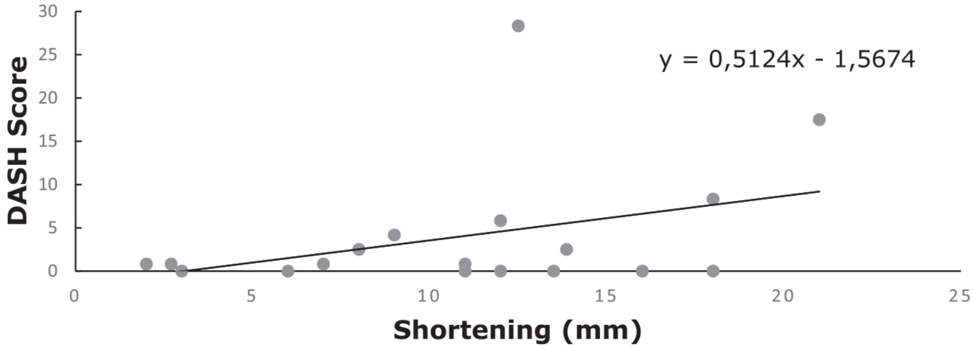

Fig. 3. DASH score plotted against relative clavicle shortening (in millimeters).

Table 2
Overview of the multiple regression analysis for external rotation

	B	SEB	β	Sig.
Intercept	-49.222	15.732		.007
Clavicle Shortening	3.098	.948	.721	.005
Affected on dominant side	24.980	10.696	.515	.034

Note. B = unstandardized regression coefficient; SEB = Standard error of the regression coefficient; β = standardized coefficient.

Table 3
Overview of the linear regression analysis for DASH in relation to external rotation strength

	B	SEB	β	Sig.
Intercept	-4.780	4.591		.313
DASH score	1.270	.552	.498	.035

Note. B = unstandardized regression coefficient; SEB = Standard error of the regression coefficient; β = standardized coefficient.

0° abducted, elbow 90° flexed), and abduction (shoulder 90° abducted, elbow 90° flexed) motion. We determined the effect of the extent of shortening on the difference in shoulder strength. Furthermore, we determined if there was any difference in the DASH score over the years. The main finding of this study was that the difference in isometric force between the affected and unaffected arm was independent of the extent of clavicular shortening in internal rotation and abduction. The effect of extent of clavicular shortening on the difference in isometric force between the unaffected and affected arm in external rotation can be regarded as negligible. We found no statistically significant difference in isometric strength between the unaffected and affected arm for both internal rotation, external rotation and abduction. This was not what we had expected based on an earlier biomechanical study (Hillen et al. 2016). This is also not in accordance with some of the earlier studies on this matter (Table 4). Ledger reported significant decreased strength for internal rotation (Ledger et al.), Su reported decreased abduction strength (Su et al. 2016), Schulz reported decreased strength for external rotation (Schulz et al. 2013) and McKee reported a significant decrease in all three directions (McKee et al. 2006).

Parry did not find any difference in strength between the affected and unaffected side either (Parry et al. 2017). In table 4 results of these studies on altered strength after malunion are listed. There are some methodological differences between these studies. Parry and Schultz specifically looked at adolescents. Hillen showed that clavicular shortening changes the anatomical geometry of the whole shoulder girdle and thus the moment arms that work over the clavicle (Hillen et al. 2016). The consequence of this would be a reduction of strength in those muscles. Ffurthermore, the length-tension relationship and the mechanical efficiency of the shoulder girdle muscles will also be decreased as a consequence of the clavicle shortening (Ledger et al.). This may have an effect on the strength-generating capacity of the shoulder muscles, as described in several studies. In a computational study on previously collected cadaveric data Hillen found a reduction in maximal producible muscle moments around the sternoclavicular joint for abduction and around the glenohumeral joint for internal rotation in resting position, when in a biomechanical simulation the clavicle was shortened (Hillen et al. 2016). The reduction was increasing with the amount of shortening with little change at 1.2 cm shortening but the decrease was significant at 2.4 and 3.6 cm of shortening. But over a longer period of time this effect can be greatly reduced by muscles having the ability to adapt to a changed situation. The length-force relationship of the muscles can change over time (De Ruiter and De Haan 2000, Jones et al. 2006, De Ruiter et al. 2016)

					Δ strength		
	N	Avg age	Avg follow up	Avg shortening	Abduction	Exo rotation	Internal rotation
Ledger et al. 2005	10	33 y	18 m	21.4 mm	5%↓ (ns)	12%↓ (ns)	15%↓ ($p<0.05$)
McKee et al. 2006	30	37 y	55 m	14.5mm	18%↓ ($p<0.05$)	19%↓ ($p<0.05$)	15%↓ ($p<0.05$)
Parry et al. 2015	8	14 y	22 m	23.8 mm	1%↑ (ns)	2%↑ (ns)	5%↑ (ns)
Su et al. 2016	14	44 y	33 m	12.9 mm	9%↓ ($p<0.05$)	5%↓ (ns)	1%↑ (ns)
Schultz et al 2013	16	14 y	24 m	13.8 mm	2.1%↓ (ns)	8.4%↓ ($p<0.04$)	7.9%↓ (ns)
Our study	18	52 y	162 m	10.9 mm	0%	1%↓ (ns)	1%↑ (ns)

Table 4: Overview of studies on altered strength after clavicle malunion

and so can the PCSA of the muscle, for example through training (Sugisaki et al. 2015). The relatively small extent of shortening in this group might also be a factor that explaines the difference with earlier studies (Table 4).

It seems that there is a threshold for shortening to become symptomatic. In earlier studies this threshold was mentioned and estimated at 1.5 – 2.0 cm (Hill et al. 1997, Nowak et al. 2004, McKee et al. 2006). The group of patients in this study had a moderately shortened clavicle (Range 0.2-2.7 cm, mean 1.09 cm, SD 0.53) with only two subjects with a shortening of more than 2 cm. This could be the explanation for the absence of significant strength reduction in our study as opposed to other studies. We expected to find a relationship between the amount of shortening and relative strength deficit in the affected arm. This hypothesis was partly based on the decrease in strength of the injured arm as a consequence of clavicular shortening on the short term, as reported in several studies (Ledger et al., McKee et al. 2006, Su et al. 2016). In a previous study Hillen reported a reduction in maximal producible muscular moments around the sternoclavicular joint for internal rotation and abduction in resting position, while the clavicle was shortened 3.6 cm (Hillen et al. 2016). However, there is little information in the literature about the effect of clavicular shortening on alteration in isometric strength on the long term. Furthermore, little is known about the relationship between the extent of shortening and its effect on isometric strength. The expectation was that the shortening of the clavicle and the associated decrease in moment arm of the muscles working over the clavicle would mainly have an effect on the strength of the affected arm in internal and external rotation and the abduction in higher abduction angles(Veeger and van der Helm 2007, Hillen et al. 2016). Therefore, isometric strength measurements in this study were performed for the internal rotation and external rotation in neutral position and the abduction motion with the upper arm abducted 90°. This study revealed a statistically significant effect of clavicular shortening and whether the fracture was on the dominant side on the isometric force difference of external rotation between the unaffected and affected arm. The greater the extent of relative clavicular shortening, the greater the strength difference between the unaffected and affected side on external rotation. Using the multiple regression model for external rotation, a clavicle shortening of 36mm would predict an isometric force difference of approximately 11 Newton between affected and unaffected side, or approximately 10% of the maximum exorotation strength. This is considerably lower than the 20% strength loss that we earlier predicted on the basis of a simulation study(Hillen et al. 2016).

The small number of participants was one of the limitations of this study, but was the logical consequence of a follow-up period of 13.5 years. From the group of 41 former participants in an earlier study only 18 participants could be included in current study. The low number of participants in this study reduces the power of the study and reduces the likelihood that a statistically significant result reflects a true effect (Button et al. 2013). As a result of the low numbers, the result of this study must be interpreted as indicative. Further research with more participants will have to confirm a true effect, but our results do indicate that these effects might be small as was the case in most of the other studies mentioned before (Ledger et al., McKee et al. 2006, Schulz et al. 2013, Su et al. 2016, Parry et al. 2017) (table 4). Another drawback of this study was the determination of shortening of the clavicle as the difference in clavicle length between the unaffected and affected side. This method can possibly be unreliable due to a natural asymmetry (up to 5mm) in clavicle length as reported by Hoogervoorst et al. (2019). Three participants in current study had a relative clavicular shortening of less than 5 mm and this shortening is therefore possibly negligible. The removal of those participants would however not have resulted in a change in effect.

This study indicates that, based on this small sample, but over a very long period of time there appears to be no reason for concern on the long term about strength losses and residual pain after conservatively treated mid-shaft clavicular fractures, be it within the shortening range of this study.

For many years there is debate in the literature about operative or conservative treatment of mid-shaft clavicular fractures. Patients also doubt whether they prefer surgical treatment or not. This doubt is partly due the risk of residual pain, weakness and strength loss of the shoulder and arm when treated conservatively (McKee et al. 2006). These short-term concerns are confirmed by several studies but operative treatments also have their drawbacks, like secondary hardware problems or infection risk (Hillen et al. 2010). Maybe correction of deformation (secondary treatment) of symptomatic malunion rather than prevention of malunion by primary surgical treatment should be the treatment protocol of preference.

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Chapter 7

Corrective osteotomy after malunion of mid-shaft fractures of the clavicle

7

Hillen RJ, Eygendaal D. Corrective osteotomy after malunion of mid-shaft fractures of the clavicle. Strategies Trauma Limb Reconstr 2007; 2(2-3):59-61.

Abstract

Displaced mid-shaft fractures of the clavicle result in some degree of shortening and rotation. These fractures often heal with some degree of malunion which can be symptomatic. The question arises as to whether surgical correction of the deformity will relieve the symptoms associated with the malunion. Ten patients with a symptomatic malunion of the clavicle were treated by means of a corrective osteotomy with plate and screw fixation. Outcome measurement was a pre and postoperative DASH score, range of motion and patient satisfaction. At follow up after a mean duration of 37 months there was a significant improvement of the DASH score, eight patients were satisfied, and range of motion did not differ significantly. Two patients had a complication resulting from the surgical procedure. Corrective osteotomy is a good treatment option for symptomatic malunion of the clavicle.

Introduction

A fracture of the clavicle is a common injury (4-12% of all fractures). Over two-third of these fractures involve the mid-shaft (Allman type I (Allman, Jr., 1967)). Conservative treatment is the method of choice for most type I fractures (Neer II, 1984), however, when displaced it usually results in some degree of shortening (Edelson, 2003,Hill et al., 1997,Nordqvist et al., 1997). Several studies show excellent results after conservative treatment (Eskola et al., 1986,Nordqvist et al., 1997,Rowe, 1968,Stanley et al., 1988) and show only cosmetic problems as a result of shortening. Recent studies using a patient-based outcome score show a less favourable outcome resulting from conservative treatment (Hill et al., 1997,McKee et al., 2003,Ledger et al., 2005). Patients complain of pain, weakness, rapid fatigability, numbness or paraesthesia of the arm and hand as well as cosmetic complaints. Nowak et al. (Nowak et al., 2004) have determined predicting factors on first presentation with regard to sequelae. Indications for primary surgical treatment of clavicular fractures include an open fracture or when the neurovascular structures are compromised (Rowe, 1968,Neer II, 1984). Severe dislocation and angulation are also considered an indication for surgical treatment as closed reduction seldom results in a sustained improvement of the alignment (Rowe, 1968). Reasons for secondary surgical treatment are delayed or non-union and malunion with sequelae (Rowe, 1968,Nowak et al., 2005,Neer II, 1984,McKee et al., 2003,Ledger et al., 2005,Edelson, 2003). We treated a group of patients who complained of pain after a malunion of the clavicle with a corrective osteotomy. The objective of this retrospective study is to determine the (long term) results of this treatment as well as the possible complications.

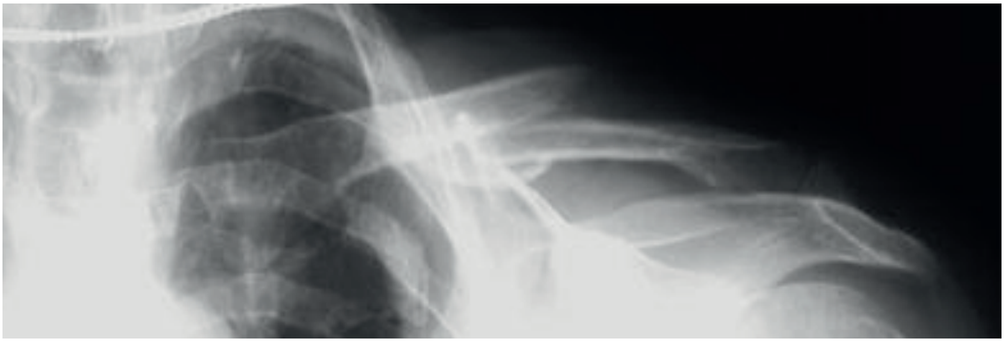

Figure 1. Malunion of a mid-shaft clavicle fracture

Materials and methods

This paper represents a retrospective study of ten patients (6 female, 4 male) with an average age of 40 years (range 21-57 years), with a symptomatic malunion of the clavicle. Surgical correction was performed using the technique described by McKee et al. (McKee et al., 2004). The approach was done through an oblique incision along the superior margin of the clavicle. After exposing the malunion, a sliding osteotomy trough the original fracture plane to correct the shortening (and rotation). The medullary canal was re-established with a drill and fixation is done with a pelvic reconstruction plate (Synthes GmbH, Solothurn, Switzerland) with 3 bicortical screws on each side of the osteotomy. The plate was placed onto the posterosuperior side (Fig 2) Bone grafting was not necessary in this group of patients. All procedures were performed by the senior author (D.E.). These patients presented at the outpatient department with ongoing pain in the shoulder region after a "healed" clavicular fracture. In 9 out of 10 patients the fracture was due to a high energy trauma (ea. Road traffic accident, horse riding accident). All had sustained a mid-shaft dislocated fracture as an isolated injury. The mean time between the fracture and the correction osteotomy was 25 months (SD 30, table I). The most important complaint these patients had was pain in the shoulder and loss of strength in the arm. We tested the pre- and post-operative shoulder function using the Disability of the Arm Shoulder and Hand (DASH) score (Hudak et al., 1996). In this scale 0 indicates a perfect function of the upper extremity, 100 is complete loss of function. A normal population has an average score of 5 (Hill et al., 1997). We determined the pre- and post-operative range of motion and complications of the surgical treatment. We asked the patients if they were satisfied with the results of the operation. The mean pre-operative score was 78 (range 53-100, SD 14.9, table I). None of these patients had signs of brachial plexus lesion. The average amount of shortening was 2.4 cm (range 1,5-3,5 cm, SD 0.8, table I) in comparison to the uninjured side as measured on a bilateral PA shoulder radiograph. Indication for surgery was ongoing pain in the shoulder with a malunion of the clavicle having a shortening of 1.5 cm or more and no other cause for the pain could be found. The follow up was done independently by the junior author (R.J.H.).

Results

A significant (p<0,005, student t-test) decrease in DASH-score was found (table I) as a result of the operation. There was no significant difference in the pre and post-operative range of motion. Patient satisfaction was tested by asking the patient whether he or she would undergo the same surgical procedure again, given the same circumstances. Eight out of 10 stated they would, one was in doubt and one would refuse. Complications were seen in 2 of the 10 patients; one sustained a deep infection, and the other had a non-union and needed further treatment. The mean follow up was 37 months (range 14-56, SD17, table I). The largest amount of decrease in DASH score was seen in patients who were operated on within one year after the fracture. The difference in DASH-score decrease with the rest of the group was significant (p<0,02) however, due to the small number of patients this difference can only be seen as a subject of interest for further study. In 7 of the 10 patients the plate and screws were removed due to symptoms.

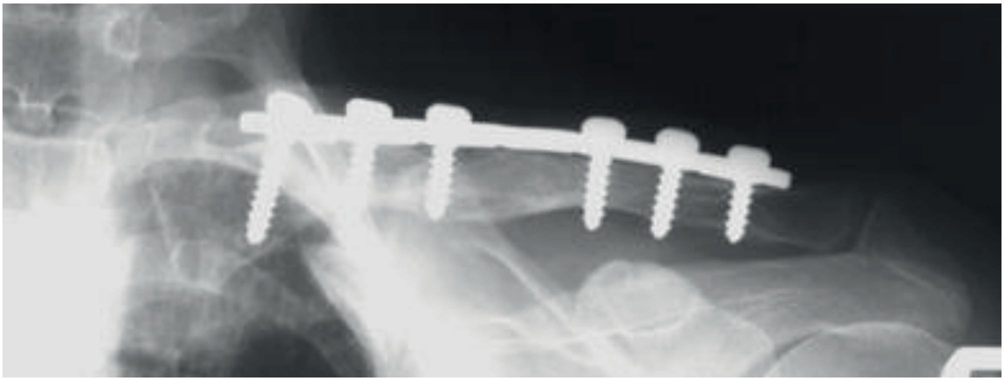

Figure 2. Situation after corrective osteotomy with plate and screws

	Shortening (in cm)	Pre operative DASH [a] score	Post operative DASH [a] score	Follow up (in months)	Complication	Time between fracture and correction (in months)
1	3.2	72	39	14	No	85
2	2.0	53	26	54	No	261
3	1.5	100	72	14	No	13
4	1.8	88	2	56	No	10
5	2.2	96	44	46	No	17
6	2.5	63	48	18	No	16
7	3.5	75	36	53	Yes	26
8	2.1	67	73	49	Yes	74
9	3.5	85	33	41	No	5
10	1.3	82	74	22	No	257
Mean	2.4	78	45	37		25
Standard deviation	0.8	14.9	23.2	17		30

Discussion

Displaced mid-shaft fractures of the clavicle all result in some degree of shortening due to opposing forces acting upon the bone. The sternocleidomastoid muscle pulls the medial fragment superiorly and posteriorly, whilst the pectoralis major muscle, the deltoid muscle and gravity pulls the lateral fragment inferiorly and anteriorly (Neer II, 1984). Traditional teaching has been that malalignment of clavicular fractures rarely causes problems. More recent studies, in which the outcome tests were more patient based rather than just radiological, show less favourable outcomes of a malunion (Hill et al., 1997,Ledger et al., 2005,McKee et al., 2003,Nowak et al., 2005). Nowak et al (2005) showed that functional impairment after a malunion with shortening is not exceptional; in a prospective consecutive series of 222 clavicular fractures 42% had sequelae at 6 months; primary displacement was the strongest radiologic risk factor(5). Our study suggests that better results can be obtained by correcting the deformity within the first year. The drawbacks of our study are the small number of patients (though one of the largest in recent literature) and the retrospective setup. Mc Kee et al (2003) showed similar outcomes to our study as do other authors (Bosch et al., 1998,Simpson and Jupiter, 1996). A clavicular fracture with significant shortening is not such a “benign” lesion as is commonly thought (Ledger et al., 2005,Nowak et al., 2005) and maybe there is an argument to perform ORIF when there is more than 20 mm (Canadian Orthopaedic Trauma Society, 2007,Hill et al., 1997,Potter et al., 2007) shortening in the young and active group. Currently we are studying the amount of symptomatic malunions in a consecutive series of conservatively treated clavicular fractures and a study where the effect of shortening of the clavicle on the biomechanics of the shoulder girdle is measured.

Conclusion

Correction after a malunion seems to be an option in case of a symptomatic malunion of a mid-shaft fracture of the clavicle, however risk of complications should be taken into consideration. A second operation to remove plate and screws is often necessary.

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Chapter 8

A simple surgical technique for correcting malunion after mid-shaft clavicle fracture

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Abstract

Clavicle malunion occurs in two thirds of all clavicle fractures treated conservatively. It can lead to pain, shoulder dysfunction and cosmetic complaints. Surgical treatment of all mid-shaft fractures will lead to overtreatment as not all malunions are symptomatic. In the past history several treatment modalities for correcting malunion of the clavicle have been described and all have been successful but none have shown superiority. We have developed a new surgical technique with excising a wedge to realign the clavicle malunion.

Introduction

The optimal treatment of clavicle malunion is a subject of ongoing debate in orthopedics. About two thirds of all clavicle fractures treated nonoperatively end up having some degree of malunion, with an average shortening of 1.2 cm (Eskola et al. 1986; Hill et al. 1997; Nordqvist et al. 1998). The shortening occurs as a result of the medializing forces of the pectoralis, the trapezoid, and the latissimus dorsi muscles pulling the shoulder girdle medially (Hillen et al. 2010). Not all malunions have an unfavorable outcome. A malunion of 1.4-2 cm is thought to have a higher chance of creating a symptomatic malunion (Nowak et al. 2004, 2005; Lazarides and Zafiropoulos 2006; Postacchini et al. 2009; Eskola et al. 1986; Hill et al. 1997). Symptoms regarding the malunion can differ from pain, loss of strength, rapid fatigue of the shoulder up to cosmetic complaints (McKee et al. 2006; Ledger et al. 2005; Rosenberg et al. 2007; Hill et al. 1997; Nowak et al. 2005). These complaints can vary from mild to severe complaints in daily life. No conservative treatment modality has been reported regarding clavicle malunion (Hillen et al. 2010). Several surgical techniques to correct the malunion have been described in the past history.

McKee (2004) described a technique, which has been most used, where a multi plane osteotomy through the original fracture is performed. Following the osteotomy, a reduction is performed. After reduction a plate is placed to retain length and create a stable situation. The plates can be placed postero-superior or antero-inferior to reduce the risks of complications. (Kloen et al. 2002, 2009, Collinge et al. 2006, Huang et al. 2007) Also intramedullary fixation has been described as a fixation option in either fracture treatment as well as with correction osteotomy (Basamania 1999, Chen and Liu 2000). Most authors describe a quite similar technique either with or without bone graft (Bosch et al. 1998; R.J. Hillen and Eygendaal 2007; McKee et al. 2004; Eismann et al. 2015; Chan et al. 1999; Rosenberg et al. 2007; Basamania 1999; Strong et al. 2019). All authors reported satisfying results following the malunion correction with improved function and fewer complaints. Mc Kee (2004) also described a sliding osteotomy in case of severe remodeling. With this technique the main focus regaining length of the clavicle.

Recently treatment of clavicle malunion has gained renewed attention with the introduction of computer assisted 3D reconstructions (Haefeli et al. 2017; Vlachopoulos et al. 2017; Cheah et al. 2018). Patient specific osteotomy guides are created using CT images of both clavicles. With this technique the contralateral clavicle is used as a reference to recreate the affected clavicle. In this way not only length is restored but also the alignment of the former fracture ends. All of the above mentioned techniques have been reported successful but none have shown superiority (Sidler-maier et al. 2018). We have developed a technique based on the sliding osteotomy with excising a wedge for more anatomic correction of clavicle malunion without the necessity of CT and 3D reconstructions or difficult multi plane osteotomy. Early results look promising.

Materials and methods

We have established five patients in the period 2013 - 2018 with symptomatic clavicle malunion after displaced mid-shaft clavicle fracture. The patients visited the outpatient orthopedics clinic at our hospital. All patients had previously sustained a high impact accident as a reason for the clavicle fracture (e.g. bicycle accident, motorbike accident). All fractures were initially treated conservatively.

The patients visited the orthopedic outpatient clinic after a mean period of 9.2 years (range 2 – 20 years). All patients experienced complaints that could be caused by malunion of the clavicle. All of the patients experienced pain in the shoulder girdle, experienced struggles in sporting activities (sports ranging from yoga to bicycle racing). One patient also had severe cosmetic complaints and one experienced numbness and paresthesia. A DASH score (Hudak et al. 1996) was taken pre and at least 3 month postoperatively

Patients had a mean radiographic shortening of 1,5 cm (range 0,9 cm – 2,8 cm). The radiographic shortenings were measured using the opposite clavicle as a reference. In all patients the orthopedic surgeon examined the clavicles and measured a shortening of at least 1 centimeter during physical examination. All surgeries were performed by the same orthopedic surgeon. (RJH)

Operative technique

Most, if not all, malunions of the mid-shaft will be with the medial end pulled superiorly and a little bit posterior and the lateral end pulled to inferior and a little anterior. Most of the deformity is in the coronal plane. Although the clavicle shortens with malunion there is usually excessive bone formation due to the callus formation between the overriding ends of the fracture. That is why removing bone with correction will aid in reconstructing the anatomy. To plan a correction, we obtain X-rays of the bilateral clavicle in 2 planes and one X-ray centered on the sternum showing both clavicles (fig 1). The uninjured clavicle serves as a reference although in normal situation there can be differences between a right and left clavicle (Sehrawat and Pathak 2016). The radiologic as well as the clinical shortening is measured and documented because radiologic shortening usually underestimates the actual shortening(McKee et al. 2004). In figure 2 We show the planned osteotomy. The planned osteotomy will be perpendicular to the plane in which the deformity exists so it will be close to the transversal plane. The osteotomy is from superolateral oblique across the malunion to inferomedial.

Figure 1. X-ray centered on the sternum showing both clavicles

The patients are placed in standard beach chair position. The affected clavicle is identified and draped free. We approach the clavicle through an incision along the skin lines with an angle about 30 degrees with long axis of the clavicle. The myofascial layer is exposed subcutaneously. The myofascial layer is opened along the clavicle (angulated about 30 degrees to the skin incision). A more standard approach parallel with the long axis for this purpose can be used also. The malunion is identified and cleared of the soft tissue so that it can be visualized. Now the line of the osteotomy can be identified and marked by electrocautery. The more shortening has occurred the longer the osteotomy can be made and hence more correction can and needs to be achieved. Now the osteotomy can be made. Once the ends are loose the ends can be further released. If we now lengthen the clavicle sliding the ends to the measured en documented length and fixing them with a reduction clamp we can see that length is corrected but an angle between the lateral and medial shaft remains. Now we measure this angle. After that we take out the reduction clamp and see if rotation between the medial and the lateral ends occur. If so this can be considered together with the shaft angle to determine the biplane angle of the wedge in the sagittal and coronal plane that needs to be removed. Now we remove a wedge from one of the ends matching that angle (figure 2). My preference is removing the wedge from the medial part as this part is displaced the most after a mid-shaft clavicle fracture. After the wedge is removed the clavicle is lengthened again and if the osteotomy ends are pressed together.

Malalignment in the transverse plane can now also be corrected (figure 3). The lengthening can now be measured from the bare osteotomy surface of the medial side that is exposed. Because of the wedge this method slightly overestimates the lengthening but not as much as the broad end of the wedge because of the correction in the vertical plane. Most of the time an anatomic clavicle plate will now fit over the clavicle or the plate can be adjusted a little. A void can be filled with bone from the removed wedge. Now a plate and screws can be applied with usually a lag screw through the plate but this depends on the plane of the osteotomy and the type of plate. Closure of the myofascial layer, subcutaneous and intracutaneous stitches. Figure 4 shows the pre and postop X-ray. The patients receive a simple sling for the first week. After that they can use the arm in daily activity but they are advised to refrain from exerting strength on the shoulder for the first 6 weeks.

Figure 2. osteotomy and correction of the malunion

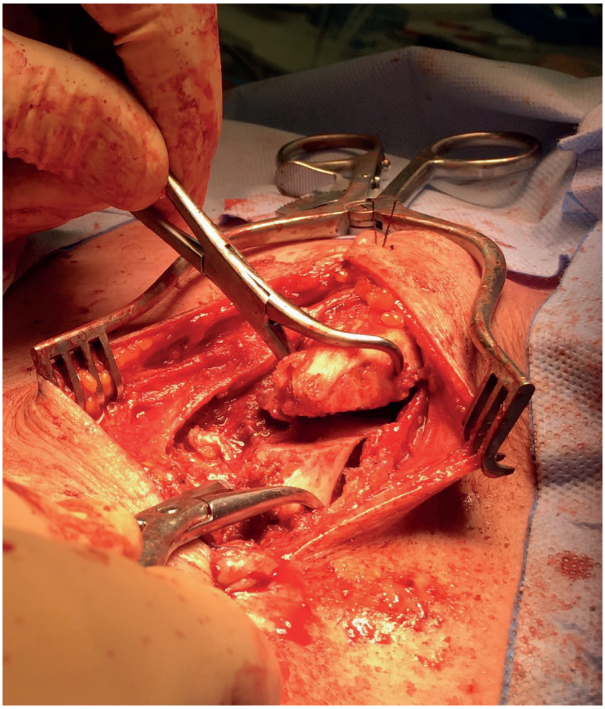

Figure 3. Exposure of the clavicle. The parallel ends of the osteotomy after the wedge has been removed. The clavicle can now be lengthened and a plate can be applied.

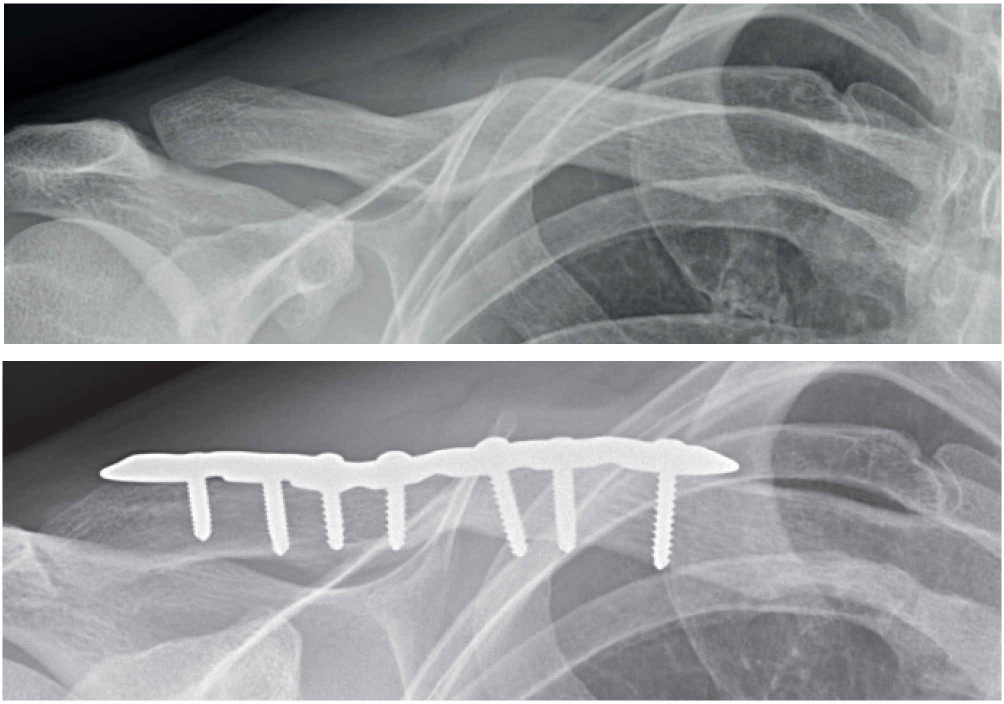

Figure 4. Situation before and after surgery

Table 1. results

Patient	Side	Dash		Radiographic shortening		Plate removal
		Preop	Postop	Preop	Postop	
1	Right	11	5	1.6 cm	0.0 cm	No
2	Right	41	5	0.9 cm	- 0.4 cm	No
3	Left	29	2	0.9 cm	- 0.2 cm	Yes
4	Left	22	8	2.8 cm	- 0.1 cm	Yes
5	Left	27	9	1.3 cm	-0,2 cm	No

Results

All but one patient were slightly under corrected (0.2 cm shortening remaining) when compared with the contralateral clavicle (Table 1). All patients had a bony union of the osteotomy within 3 months of the surgery. We did not have any complications in this group. Dash scores at an average of 8.4 month (range

3 to 18) showed significant improvement. All patients were satisfied with the outcome and would undergo surgery again now knowing the outcome.

Discussion

In this surgical note a new technique for the treatment of clavicle malunion is described. The symptomatic clavicle malunion has been described by many authors before (McKee et al. 2003; Eskola et al. 1986; Hill et al. 1997; Nowak et al. 2004; Ledger et al. 2005; Zlowodzki et al. 2005; Lazarides and Zafiropoulos 2006). Several authors have described successful surgical techniques to treat these symptomatic malunions, but none have shown superiority (Sidler-maier et al. 2018). We have applied this technique in 5 patients and early results look promising with on average over 20 points decrease of DASH score.

The surgical technique as described as above is an altered version of the sliding osteotomy technique described by McKee (2004). It is a relatively simple technique which requires plane X-rays, no additional equipment or scans. Therefore, it is an inexpensive technique. As mid-shaft clavicula fractures are extra articular fractures and the deformity in malunion is predictable we suggest our simpler, but for this purpose just as effective, technique.

The advantages of the 3D reconstructions technique in complex reconstructive surgical cases are clear, but in the case of clavicle malunion it seems to be unnecessary complicated.

In conclusion, the surgical technique as described in this paper seems to be a good option in the treatment of clavicle malunion. The first results look promising and the technique does not require additional equipment or examination. Further comparative research between all techniques should be done to show which technique is superior.

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Chapter 9

General discussion

9

General discussion

The goal of this thesis was to determine if a malunion of the clavicle is relevant from a biomechanical and clinical point of view. We assessed the altered biomechanics of the shoulder girdle after shortening of the clavicle, the incidence of symptomatic malunion as well as risk factors for developing a symptomatic malunion. As there is much debate in the recent literature about the optimal treatment strategy for acute displaced mid-shaft clavicle fractures we aimed to give an evidence-based treatment rationale. We have established that shortening of the clavicle changes the biomechanics of the shoulder. In our clinical studies however only a minority of patients with a malunion of the clavicle have serious complaints of their shoulder. Treating this minority of patients with a symptomatic malunion by correcting the deformity does alleviate the symptoms. The new insights from these studies combined brings new perspective to the discussion whether or not to treat a displaced mid-shaft clavicle fracture operatively.

In the last two decades several studies have been published (Kong et al., McKee, Robinson et al., Smekal et al., Hill et al. 1997, Nowak et al. 2004, 2005, Zlowodzki et al. 2005, McKee et al. 2006) that challenge the validity of the original concept that mid-shaft clavicle fractures seldom need surgical intervention. In the group with displaced mid-shaft clavicle fractures there is a higher than previously expected number of non-union and all others result in some degree of malunion. Malunion was before these new studies never regarded as a problem (Hillen et al. 2010). Malunited mid-shaft clavicle fractures have been reported to cause several complaints in 4 to 30% of these patients (Hillen et al. 2010). Patients complain of pain, loss of strength, rapid fatigability, numbness or paresthesia of the arm and hand, problems with sleeping on the back as well as cosmetic complaints. In **chapter 2** we can see that in the current literature there are several hypotheses on what the cause of these complaints is. These can be divided into five groups: Glenoid orientation, Muscular problems, Neurovascular problems, Impingement problems and AC / SC joint problems. It is very likely that most if not all of these factors play a role in some extend in the experienced problems after malunion of a mid-shaft clavicle fracture. Our hypotheses were that malunion can give rise to significant symptoms which will most likely be related to the change in the glenoid orientation and the altered maximal muscle moments because of shortening of the clavicle.

The study of the literature (**chapter 2**), biomechanical studies (**Chapter 3 and 4**) and clinical studies (**chapter 5, 6, 7 and 8**) combined have given us more insight on the subject of clavicle malunion. From a study of the literature we learned that malunion occurs in all displaced fractures end up in a malunion or nonunion if not treated operatively. Nonunions of mid-shaft clavicle fractures occur in about 5% of all patients. With an incidence of mid-shaft clavicle fractures of about 60/100.000(Khan et al. 2009) the incidence of symptomatic malunion (4-30% of all mid-shaft fractures (Hillen et al. 2010)) can thus be estimated to be between 3 and 18 per 100.000. In the Netherlands this would mean between 480 and 2900 symptomatic malunions each year.

From our biomechanical cadaver studies, we learned that, as expected, shortening of the clavicle does alter the biomechanics of the shoulder. The orientation of the scapula relative to the thorax is changed in more lateral rotation and protraction with a decreased posterior tilt. This changes the position and orientation of the glenoid relative to the thorax. A changed orientation of the glenoid changes the direction of the joint reaction force related to the global coordinate system but the local orientation of the muscles working over the glenohumeral and AC joint does not change. Thus, there is a change of the working arm of the rotator cuff muscles relative to gravity (if the posture stays the same), resulting in a change in the stability requirements for the glenohumeral joint. This should not necessarily pose a problem if the neuromuscular system can adapt to the new situation. Our results in chapter x on the long-term effects seem to indicate that this is the case.

We used the data of the cadaver study in Delft shoulder and elbow model to see if we could predict what the altered biomechanics effect would be on strength of the shoulder, as a shortened clavicle would also lead to a shorter "spinnaker pole" of the shoulder relative to the trunk. In the model we did see changes in strength of the shoulder girdle with shortening of the clavicle. The maximal muscle moments around the glenohumeral joint for internal rotation and for ab and adduction around the sternoclavicular joint are significantly reduced with shortening of the clavicle in this study.

In the clinical studies of this thesis (**chapter 5, 6, 7 and 8**) we looked at the incidence of symptomatic malunion in a consecutive series of patients with a mid-shaft clavicle fracture that were managed non-operatively. We tried to identify factors at initial presentation that could predict symptomatic malunion. Although we could not isolate a predicting factor, we did see that with long follow up DASH scores improved for patients that suffered a malunion. The incidence of symptomatic malunion was lower than expected (**Chapter 5**). In **chapter 4**, the experimental study on strength with shortening of the clavicle, we found reduction of internal rotation and abduction maximal muscle moments. Putting this hypothesis to the test in the group of conservative managed mid-shaft clavicle fractures, we could not confirm this strength loss by testing the strength of these patients. With the studies on this group of patients from the consecutive series of mid-shaft clavicle fractures we see few problems arising from conservative treatment. This was different from what we would expect from our experimental studies on biomechanics (**chapter 3 and 4**). A number of reasons can be an explanation for this difference. The patients in the study group were of relatively high age. The average magnitude of shortening was lower in our patient group than reported in other studies on consecutive series of patients (Hill et al. 1997, Nowak et al. 2005). The magnitude of shortening is correlated to reduction of maximal muscle moments with shortening of the clavicle. With minor shortening you would expect little change in maximal muscle moments. This group had a long follow up so adaptation of muscles to the new situation might have occurred. With a reduced moment arm a muscle can compensate for reduction of maximal muscle moment by increasing the strength of the muscle. Mankind has the ability to adapt and compensate for changes in the musculoskeletal system. To what extent this can be achieved in clavicle malunion remains unclear. A clinical study by Stegeman et al. (2015) had similar findings on functional outcome of clavicle malunion. In another group of patients that presented with symptomatic malunion we did see good improvement from correcting the deformity (**chapter 7 and 8**).

With our research we showed that shortening of the clavicle will lead to profound changes in the geometry of the shoulder girdle. The magnitude of shortening was a factor influencing biomechanical changes and altered strength in our biomechanical studies. Shortening as a risk factor for symptomatic malunion or reduced strength could however not be confirmed by our clinical studies. In our series in the long run most patients heal uneventful with conservative treatment. All in all, it seems like short malunion of the clavicle does not give rise to significant problems. This is supported by Malik et al. (2019) in a recent review study on outcome of non operative management of mid-shaft clavicle fractures, who concluded that *"There is no significant association between fracture shortening and nonunion rates or shoulder outcome scores in displaced mid-shaft clavicle fractures managed nonoperatively"* With a change of opinion in the literature on operative treatment of clavicle fractures, operative treatment of mid-shaft clavicle fractures has gained popularity in the Netherlands (Hulsmans et al. 2014). Prevention of a symptomatic malunion in the acute fracture phase by surgical treatment would have been the best option for patients with a symptomatic malunion after a mid-shaft clavicle fracture. To achieve this, we need to know if a patient will develop a symptomatic malunion but we lack proper selection criteria to predict which patients are at risk for developing symptoms after malunion. If we operate on all dislocated mid-shaft clavicle fractures a lot of patients (over 70%) will probably not have much benefits over conservative treatment whereas they will be at risk for surgical complications, have a surgical scar for the rest of their live and often a second operation to remove the hardware is necessary.

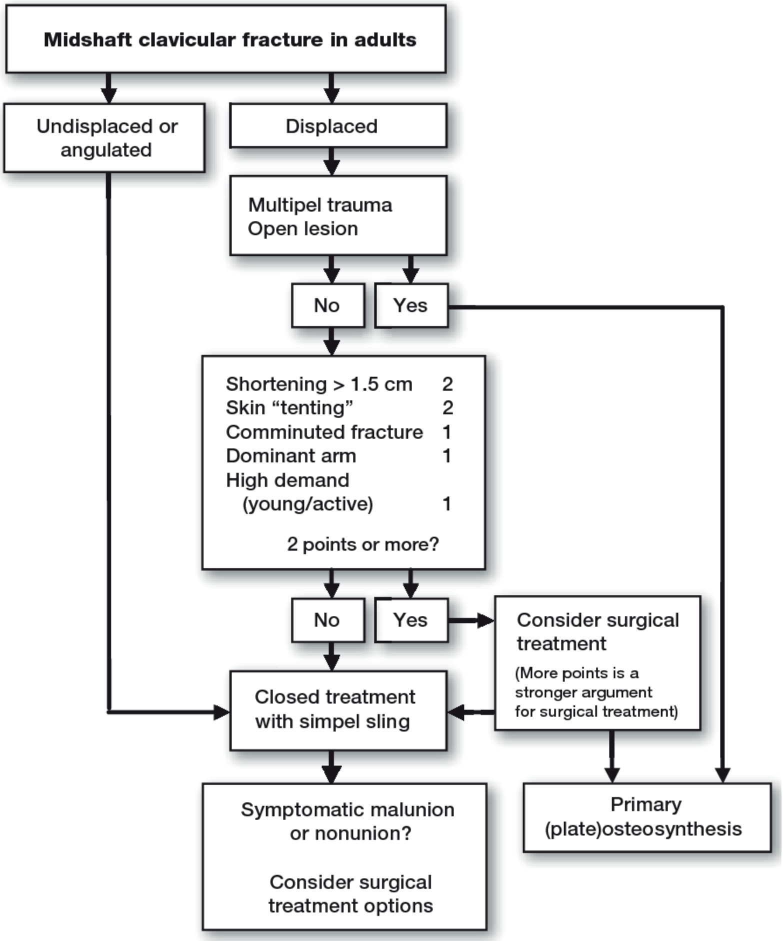

Figure 1. Suggested treatment rationale

Based on the results of this thesis, primary operative treatment to prevent symptomatic malunion should probably not be the treatment of first choice for displaced mid-shaft clavicle fractures. Surgical treatment can be chosen for other goals such as better short term results for high demanding patients (Hoogervorst et al. 2018) The flow chart in **chapter 2** can serve as a guideline but we did not find a good predictive factor to select patients that can best be treated with primary surgical treatment. In making the decision one has to consider the secondary treatment option to correct the deformity in a symptomatic malunion as well as the opinion of the, well informed, patient to come to a shared treatment decision. In this way, the number of patients that would need surgical treatment can be reduced. Delaying surgery to the point where symptomatic malunion or non-union occurs does not negatively influence the outcome (Potter et al. 2007). It is therefore a viable option with good outcome (Strong et al. 2019).

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Chapter 10

Summary and conclusion in English and in Dutch

Summary

The perception on clavicle fractures has shifted in the last 3 decades from a fracture that seldom causes problems to the realization that patients can indeed suffer sequelae after a united midshaft clavicle fracture. Midshaft clavicle fractures seldomly heal in their anatomic position. The fracture ends slide over one another resulting in shortening of the clavicle. In this position the fracture heals. Without surgical intervention the shortening cannot be prevented. In the past success of treatment outcome of clavicle fractures was measured in fracture union and range of motion afterwards. Nowadays shoulder function in daily activities is measured with questionnaires (patient-based outcome scores). These questionnaires tell us that fracture union and a full range of motion does not always need to be regarded as a successful outcome. Patients report symptoms such as pain, loss of strength, rapid fatigability, paraesthesiae of the arm and hand, problems with sleeping on the back because of altered scapula position as well as cosmetic complaints. These symptoms however are only reported by a small part of the group of patients after healing of a midshaft clavicle fracture. The majority report little or no complaints on these questionnaires.

Since surgical treatment is the only way to prevent shortening of the clavicle after a dislocated midshaft clavicle fracture one could decide to operate on all of these patients. This would however be unnecessary in most of the cases. Surgical treatment also has downsides, such as the risks of operation and a high cost of treatment, and must be prevented if unnecessary. In our studies we tried to gain insight into the alteration of biomechanics of the shoulder with shortening of the clavicle to understand what could be the cause of complaints around the shoulder with clavicle malunion. A retrospective study was performed into patient and fracture characteristics at the time of fracture. We looked at the group that suffer from sequelae afterwards to see if they share certain of these characteristics distinct from the rest of the group and so isolate characteristics that could predict symptomatic malunion. The biomechanical changes are evident. Shortening of the clavicle results in an altered position and motion tract of the scapula. Using these data in a computer model we could see that the changes of scapula position and motion would lead to less ability to generate force in certain movements of the shoulder.

Putting this hypothesis to the test showed however that in patients that patients with a malunion of the clavicle for several years we could not measure significant strength difference between the affected and the contralateral shoulder. All in

all, it seems that in seems that only a small number of patients report serious complaints with malunion of the clavicle.

Unfortunately, we could not find a solid predicting factor for symptomatic malunion as outcome of conservative treatment.

A group of 10 patients with symptomatic malunion was treated with an osteotomy to correct the length of the clavicle. This treatment showed excellent outcome. A (new) surgical technique for this operation is also described in this thesis.

The conclusion can be made that refraining from primary surgical treatment is a wise decision in the majority of patients with a midshaft clavicle fracture. The cases that end up in a symptomatic malunion can be successfully treated with an osteotomy to correct the deformity after a midshaft clavicle fracture ("Malunion of the clavicle")

Nederlandse samenvatting

De manier waarop er naar sleutelbeenbreuken wordt gekeken is in de laatste 30 jaar veranderd van een fractuur die eigenlijk altijd herstelt zonder behandeling naar een letsel die wel degelijk problemen kan geven. Een breuk van het sleutelbeen geneest vaak niet in de oorspronkelijke positie. De uiteinden van de breuk schuiven over elkaar waardoor het sleutelbeen korter wordt en in deze positie geneest de fractuur. Zonder operatie is het niet mogelijk deze verkorting tegen te gaan. Vroeger werd er gekeken of de breuk was vastgegroeid en of de schouder daarna goed kon bewegen. Nu wordt er meer gekeken naar de functie van de schouder in het dagelijks leven op basis van scorelijsten die een patiënt invult. Hieruit komt naar voren dat een vastgegroeide fractuur met goede bewegelijkheid van de schouder niet altijd als een succesvolle uitkomst moet worden beschouwd. Patiënten geven aan pijn of krachtsverlies te ervaren, een versnelde vermoeidheid van de arm te hebben bij dagelijkse taken en soms tintelingen in de arm te ervaren of moeite te hebben met slapen op de rug door de stand van het schouderblad. Ook cosmetische problemen door veranderde schouder contour worden gerapporteerd. Deze problemen doen zich echter alleen voor bij een deel van de patiënten met een genezen sleutelbeenbreuk. De meerderheid scoort ook op deze vragenlijsten goed en geven weinig tot geen problemen aan.

Gezien preventie van verkorting alleen te bereiken is met een operatie kan je ervoor kiezen alle patiënten met een verkorte sleutelbeenbreuk direct te opereren. Het zou echter in een groot aantal gevallen niet nodig zijn. Een operatie is daarbij ook niet volledig vrij van risico's en zorgt voor hoge kosten van behandeling en moet dus, indien onnodig, vermeden worden. Met onze studies hebben we geprobeerd duidelijk te krijgen wat er precies verandert in de biomechanica van de schouder als het sleutelbeen korter is geworden om zo beter te begrijpen wat de oorzaak is van klachten rond de schouder bij verkort genezen sleutelbeenbreuken. Daarnaast hebben wij retrospectief gekeken naar kenmerken van patiënten ten tijde van het oplopen van een sleutelbeenbreuk en vervolgens te kijken of de groep patiënten die klachten overhield aan de fractuur bepaalde kenmerken met elkaar gemeen hadden om zo voorspellende kenmerken te isoleren. De biomechanische veranderingen in de schouder zijn er zeker. De verkorting van het sleutelbeen levert een veranderde positie en bewegingstraject van het schouderblad op. In een computermodel kon met deze verkregen data ook worden aangetoond dat de veranderingen ook zullen leiden naar een vermindering van het vermogen om kracht te genereren in de schouder in een bepaalde bewegingsuitslag.

Toen we deze data in de praktijk toetsten bij patiënten met een verkort genezen sleutelbeenbreuk na een fractuur meerdere jaren geleden, konden we echter geen significant krachtverlies ten opzichte van de gezonde kant meten. Überhaupt blijkt de incidentie van klachten na een verkort genezen sleutelbeenbreuk in de praktijk nogal mee te vallen.

Helaas konden we geen duidelijke risicofactor benoemen die het ontwikkelen van klachten na een verkort genezen sleutelbeenbreuk kan voorspellen.

Bij een groep van 10 patiënten met klachten na verkort genezen sleutelbeenbreuk is een operatie uitgevoerd om het lengte verlies te herstellen. Dit gaf hele goede resultaten. Een (nieuwe) techniek om deze operatie uit te voeren wordt ook nog beschreven in dit proefschrift.

Concluderend kan worden gesteld dat terughoudendheid om tot operatie over te gaan bij een breuk van de clavicula een verstandige keuze is in de meeste gevallen. Voor de patiënten die achteraf toch klachten houden is er een goede behandeloptie beschikbaar om het verkort genezen sleutelbeen fractuur ("Malunion of the clavicle") weer te reconstrueren.

Chapter 11

Dankwoord/
Curriculum vitae

Dankwoord

Geachte lezer,

Allereerst dank aan u voor de getoonde interesse in mijn werk. Wat u voor u heeft is de voltooiing van een karwei dat in 2005 is gestart. Het begon met een eerste artikel omdat ik naast het klinische werk ook wetenschappelijk werk behoorde te leveren. Het eerste onderzoek leverde naast een aantal inzichten (het wordt tot op heden nog steeds geciteerd) mij ook een hoop nieuwe vragen op. Verandering van werkplek en nieuwe begeleiders gaven ruimte en impuls om verdere onderzoeksvragen te formuleren en op te pakken. Het proces van nieuwe inzichten en nieuwe vragen bleef zich herhalen. Nieuw onderzoek volgde. De ambitie ontstond om er een promotietraject van te gaan maken. Dat bleek een tijdrovender klus dan verwacht en het was naast een proeve van bekwaamheid in het bedrijven van wetenschap dan ook vooral een les in volharding en doorzettingsvermogen. De samenwerking en begeleiding die ik heb mogen ontvangen van een aantal getalenteerde, geïnteresseerde en motiverende mensen heb ik als een voorrecht ervaren en wil ik hier dan ook niet ongenoemd laten.

Beste Dirkjan, in literatuuronderzoek kwam ik een publicatie tegen waar ik zeer van onder de indruk was. Toen ik het las begreep ik meteen dat de auteur de biomechanica en complexiteit van de schouder als geen ander begreep. Toen ik vervolgens de auteur opzocht en deze bleek, stomtoevallig, aan de VU te zijn verbonden heb ik contact met je gezocht. Met twee gevulde koeken voor bij de koffie kwam ik bij je langs. We hebben zo nog vele keren gezeten en verscheidene koeken verorberd. Mijn respect voor jouw kennis en kunde van de biomechanica van de schouder is daarna alleen maar toegenomen. Je toegankelijkheid en enthousiasme om samen dit project op te pakken en je creativiteit hebben me erg geholpen. Jouw inbreng voor de biomechanische studies was onmisbaar en je hebt mij een hoop geleerd. Iets minder waardering had ik soms wel eens voor je rode pen maar jouw kritische commentaar heeft de kwaliteit van het proefschrift enorm vergroot en mij behoed voor mijn karaktertrek om het op de makkelijke manier te doen.

Beste Denise, plezier in werk met eindeloze energie lijkt jouw drijfveer. Dit werkt besmettelijk en je hebt zo al talloze mensen om je heen aangestoken. Je hebt aan de wieg van dit project gestaan met onze eerste publicatie. Jij gaf me het duwtje in de rug om wetenschappelijk aan de slag te gaan en gaf me dit onderwerp aan. Dat dit hierin zou uitmonden voorzagen we beide niet. Ik ben je veel dank verschuldigd voor deze duw in de juiste richting. Door mijn hele carrière heb ik erg veel aan je gehad. Je begeleiding en vertrouwen die ik als assistent van je kreeg en later ook bij mijn fellowship in Breda. Even overleg bij een lastige casus. En nu je rol als promotor. Ik hoop ook in de toekomst nog veel met je te mogen samenwerken.

Beste Bart, je bent voor mij een mentor, een voorbeeld en een vriend. Toen ik als AIOS weer in Alkmaar kwam was jij het die aangaf na mijn eerste publicatie over clavicula malunion door te pakken op dit onderwerp en samen zetten we de retrospectieve studie op. Voor zowel je bijdrage aan het onderzoek en het inzetten van hulptroepen ben ik je veel dank verschuldigd. De mogelijkheden, ondersteuning en stimulans om onderzoek te doen in Alkmaar zijn ongekend en hebben mij ontzettend geholpen om het onderzoek op de rails te krijgen met als doel dit proefschrift. De vele andere publicaties van andere assistenten uit Alkmaar zijn hier ook getuige van. Daarnaast je (vaderlijke) rol als opleider, werken op basis van vertrouwen en mensen zo stimuleren om het beste uit zichzelf te halen, was een feest om te mogen ervaren na mijn ervaring elders.

Beste Ruud, jij was initieel de promotor van mijn project en dat is precies de houding die je ook altijd hebt aangenomen. Je hebt altijd op positieve wijze mijn werk gestimuleerd. Je ingezet om mij de kans te geven dit onderzoek af te ronden zonder moordende deadlines. Je begreep dat dit werk naast gezin en werk moest gebeuren. Ik denk dat dit in belangrijke mate eraan heeft bijgedragen dat ik niet het bijltje erbij neer heb gegooid. De voltooiing heeft lang op zich laten wachten maar is nu toch een feit. Het rustige tempo (en wat tegenslag) heeft er wel in geresulteerd dat je, nu ruim 5 jaar met emeritaat, je rol als promotor niet meer mag vervullen. Ik ben blij dat je als copromotor nog wel betrokken bent.

Leden van de promotiecommissie, Prof Dr Ir J. Harlaar, Prof Dr R.G.H.H. Nelissen, Prof Dr A. van Kampen, Dr A.C.H. Beumer, Dr M.J.M. Hoozemans, ik ben u allen zeer erkentelijk voor het (herhaaldelijk) beoordelen van mijn manuscript.

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Alle andere medeauteurs, hier niet specifiek genoemd, wil ik ook danken voor hun bijdrage aan de verschillende publicaties.

De proefpersonen wil ik hier ook bedanken voor hun belangeloze meewerken door (allereerst hun sleutelbeen te breken) vragenlijsten invullen en metingen te ondergaan.

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het mij weer kunnen motiveren na commentaar te hebben moeten incasseren van reviewers. De achterliggende jaren met jou, waarin dit boekje tot stand is gekomen, waren een mooi avontuur. Ik ben heel blij met alles wat je me hebt gegeven. Je vult me aan in mijn tekortkomingen (dat is best een klusje!) en ik geniet nog altijd van onze tijd samen met ons mooie gezin.

Curriculum Vitae

Robert Jan Hillen, de auteur van dit proefschrift, is geboren op 3 november 1971 te Groningen. Na het behalen van zijn vwo-diploma in 1992 werd hij uitgeloot voor de studie geneeskunde en startte hij in 1993 met de studie geneeskunde aan de Rijks universiteit Groningen. De co-schappen heeft hij in het Sint Elizabeth hospitaal in Willemstad te Curaçao doorlopen tussen 1998 en 2000. Daarna werd een keuzecoschap orthopedie in het OLVG doorlopen. Zijn eerste baan na zijn studie was Senior house officer of the orthopedic department Royal Treliske hospital, Truro, Cornwall, UK. Na 4 maanden kwam hij terug om in het Medisch Centrum Alkmaar aan de slag te gaan. Na bijna een jaar AIOS te zijn geweest in Alkmaar begon hij met zijn vooropleiding heelkunde in het Diaconessenhuis te Utrecht onder leiding van Dr G.J. Clevers. Daarna werd met de orthopedie opleiding begonnen in de St Maartenskliniek in Nijmegen en het Rijnstate ziekenhuis te Arnhem. In de St Maartenskliniek is het onderzoek voor het eerste artikel van dit proefschrift verricht. Na een periode hier is hij teruggegaan naar Alkmaar om daar onder leiding van Dr B.J. Burger zijn opleiding te vervolgen. Het academische jaar werd doorlopen aan de Vrije Universiteit in Amsterdam onder leiding van Prof. dr. B.J. van Royen. Hier is het contact ontstaan met Prof Dr R.G. Pöll en prof dr H.E.J. Veeger om de begeleiding van het promotie traject op zich te nemen. Na waarneming in het Slotervaart ziekenhuis te Amsterdam, een fellowship bovenste extremiteit in het Amphia ziekenhuis te Breda onder leiding van Prof Dr D Eygendaal, chef de clinique in het AMC in Amsterdam werkt Robert Jan nu 10 jaar in de orthopedie vakgroep van het Dijklander ziekenhuis te Hoorn en Purmerend. Hij is getrouwd met Laurien Schönhuth en samen hebben ze vier zonen: Berend, Valentijn, Zeger en Ingmar.