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The biomechanical effect of clavicular shortening on shoulder muscle function, a simulation study

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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 sterno-clavicular joint decreased for both ab- and adduction, 37% increased around the acromion-clavicular joint for adduction and 32% decrease for internal rotation around the gleno-humeral 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

1. Introduction

Midshaft 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 midshaft 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 gleno-humeral 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 gleno-humeral 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 1.2 cm, with a range up to 3 cm (Eskola et al., 1986; Hill et al., 1997; Nordqvist et al., 1997). This will 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

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available at the moment. This study by Patel et al. (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 et al. (Patel et al., 2012) showed a change in muscle potential around the GH after shortening. We fely 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 effect 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 (Patel et al., 2012; Chan et al., 1999; Ledger et al., 2005). 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, 2011) to quantify the effect of clavicle shortening on maximal muscle moment for the GH, SC and acromion-clavicular 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.

2. Methods

2.1. 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 5 Hz. 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.

2.2. 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.

2.3. 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:

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

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 $\sigma_{\max}$ 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