The analysis of 3D scapular kinematics and EMG of the scapulothoracic muscles in patients with midshaft clavicle fractures

A descriptive laboratory study

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Master’s dissertation submitted to Ghent University in order to obtain the degree of Master of Rehabilitation Sciences and Physiotherapy

Academic year: 2020 – 2021
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A descriptive laboratory study
Dankwoord

Met trots schrijven we dit dankwoord als einde van onze masterproef. Het volmaken van deze masterproef zou nooit mogelijk geweest zijn zonder de steun en samenwerking van verschillende mensen.

Als eerste willen we graag onze promotor Prof. Ann Cools bedanken om ons de mogelijkheid te geven ons te verdiepen in dit onderwerp.

Bijzondere dank gaat ook uit naar onze copromotor Kelly Berckmans voor de goede begeleiding, de nuttige tips en de uitgebreide feedback.

Tevens willen we ook graag Lisa Bernaers bedanken voor de samenwerking tijdens mevrouw Berckmans haar zwangerschapsrust. We konden altijd bij haar terecht met onze vragen en werden telkens zo goed mogelijk geholpen. Hartelijk dank voor de vlotte samenwerking.

Graag willen we ook de dokters en ziekenhuizen (UZ Gent en AZ Sint-Jan Brugge) bedanken die het mogelijk maakten om patiënten te rekruteren.

Aansluitend bedanken we ook de proefpersonen die tijd wilden vrijmaken om deel te nemen aan deze studie. Zonder hen was er geen sprake geweest van deze studie.

Tot slot willen we graag onze ouders, vrienden en familieleden bedanken voor hun ondersteuning, begrip en het nazicht van deze masterproef op taal- en schrijffouten. Eveneens houden we een goed gevoel over aan onze vlotte samenwerking van de afgelopen twee jaar.

Het indienen van deze masterproef zorgt ervoor dat we onze studies Revalidatiewetenschappen en Kinesitherapie in schoonheid kunnen afsluiten.

Gent, mei 2021

Lara Smis
Kaat Stepman
Justine Stevens
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<th>Description</th>
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</thead>
<tbody>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>BMI</td>
<td>Body Mass Index</td>
</tr>
<tr>
<td>CON</td>
<td>Concentric</td>
</tr>
<tr>
<td>CS</td>
<td>Constant Shoulder score</td>
</tr>
<tr>
<td>DASH</td>
<td>Disability of the Arm, Shoulder and Hand questionnaire</td>
</tr>
<tr>
<td>ECC</td>
<td>Eccentric</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IS</td>
<td>Injured side</td>
</tr>
<tr>
<td>ISB</td>
<td>International Society of Biomechanics</td>
</tr>
<tr>
<td>LT</td>
<td>Lower trapezius</td>
</tr>
<tr>
<td>mm</td>
<td>Millimeter</td>
</tr>
<tr>
<td>MT</td>
<td>Middle trapezius</td>
</tr>
<tr>
<td>MVIC</td>
<td>Maximal voluntary isometric contraction</td>
</tr>
<tr>
<td>NIS</td>
<td>Non-injured side</td>
</tr>
<tr>
<td>Pm</td>
<td>Pectoralis minor</td>
</tr>
<tr>
<td>PMI</td>
<td>Pectoralis minor index</td>
</tr>
<tr>
<td>SA</td>
<td>Serratus anterior</td>
</tr>
<tr>
<td>SPM</td>
<td>Statistical Parametric Mapping</td>
</tr>
<tr>
<td>SPM{t}</td>
<td>SPM paired t-test</td>
</tr>
<tr>
<td>UT</td>
<td>Upper trapezius</td>
</tr>
</tbody>
</table>
Abstract (English)

**Background:** Clavicular fractures are one of the most common skeletal injuries and account for 2-5% of all adult fractures. Eighty percent of the clavicle fractures occur at the middle third of the bone. In general, clavicle fractures can be treated operatively or nonoperatively, depending on the characteristics of the patient and the fracture. When looking at functional outcomes, there is conflicting evidence about the best choice of treatment. The functional outcomes are mainly the result of normal underlying shoulder biomechanics and of adequate scapulothoracic muscle activity.

**Objective:** Up to now, there is a lack of information on whether a clavicle fracture would cause a difference in clavicle or pectoralis minor (Pm) length, a change in shoulder biomechanics or a modification in the function of the scapulothoracic muscles and what the impact would be. Therefore, the aim of this study was threefold: to determine differences in (i) scapular motion and (ii) scapulothoracic muscle activity during active elevation between the injured side (IS) and non-injured side (NIS) of patients with a midshaft clavicle fracture and (iii) correlations were investigated between clavicle length or Pm length with scapulothoracic muscle activity.

**Study Design:** A descriptive laboratory study.

**Methods:** Electromyography (EMG) activity of the upper trapezius (UT), middle trapezius (MT), lower trapezius (LT) and serratus anterior (SA) was synchronously measured with the scapular three-dimensional kinematics during elevation in three planes (frontal/ scapular/sagittal). This was executed for both the IS and NIS. To compare three-dimensional (3D) scapular kinematics between the IS and NIS, a curve analysis was executed using statistical parametric mapping (SPM). In addition, the clavicle and Pm length were measured to determine the correlation with the activity of scapulothoracic muscles.

**Results:** In general, the scapular motion showed the normal pattern of progressive upward rotation and posterior tilt on both sides. Although, a decreased posterior tilt of the IS compared to the NIS in the frontal and sagittal plane was found. Internal/external rotation differed depending on the plane of elevation. In all three planes, EMG analysis revealed in general a slightly increased activity of the MT and LT and a slightly decreased activity of the UT on the IS compared to the NIS. The SA of the IS showed in all three planes a slightly reduced activity during arm raising, whereas a slightly increased activity of the SA can be observed during arm lowering. In the frontal plane, the LT of the IS was significantly more active than the NIS (p<0.05).
A positive correlation (p<0.05) was found between the length of the clavicle of the IS and the activity of the SA on the same side, in the three planes. At the NIS, a negative correlation was found between the MT and the clavicle length in the three planes.

**Conclusion:** These results prove that there is no reason to choose surgical treatment over conservative treatment to restore the scapular biomechanics. Future research is needed to compare conservative treatment with operative intervention in order to detect the cause of the minimal differences in our results.

**Keywords:** midshaft clavicle fracture – conservative treatment – 3D scapular kinematics – EMG – scapulothoracic muscles
Abstract (Dutch)

Achtergrond: Claviculafracturen zijn een van de meest voorkomende botletsel en vertegenwoordigen 2-5% van alle fracturen bij volwassenen. Tachtig procent van alle claviculafracturen ontstaan in het middelste derde van het bot. Deze fracturen kunnen operatief of non-operatief behandeld worden afhankelijk van de kenmerken van de patiënt en de fractuur. In de literatuur is er verdeeldheid over de beste keuze van behandeling op vlak van functionele outcome. Deze functionele outcomes zijn hoofdzakelijk het resultaat van een normale onderliggende schouderbiomechanica en van adequate activiteit van de scapulothoracale spieren.

Doel: Tot op heden is er een gebrek aan informatie over de mogelijke effecten van een claviculafractuur en de impact hiervan. Mogelijke veranderingen zijn bijvoorbeeld een verschil in claviculalengte of pectoralis minor (Pm) lengte, een verandering in de biomechanica van de schouder of een wijziging in de functie van de scapulothoracale spieren. Daarom had deze studie als doel om de verschillen te bepalen in de scapulaire beweging en scapulothoracale spieractiviteit tussen de conservatief behandelde zijde en de gezonde zijde van patiënten met een midshaft fractuur. Dit werd geanalyseerd tijdens een actieve elevatie in drie verschillende vlakken. Een ander doel van deze studie was de correlatie nagaan tussen enerzijds de claviculalengte en Pm lengte en anderzijds de scapulothoracale spieractiviteit.

Onderzoeksdesign: Een beschrijvend laboratoriumonderzoek.

Methode: De elektromyografische activiteit van de drie trapezius bundels (trapezius pars descendens (UT), trapezius pars transversa (MT) en trapezius pars ascendens (LT)) en serratus anterior (SA) werd gelijktijdig geregistreerd met de scapulaire driedimensionale kinematica tijdens elevatie in drie vlakken (frontaal/scapulair/sagittaal). Deze metingen werden uitgevoerd voor zowel de aangedane zijde (AZ) als de niet-aangedane zijde (NAZ). Om de driedimensionale scapulaire kinematica te vergelijken tussen beide zijden werd gebruikt gemaakt van de statistical parametric mapping (SPM) methode. Aanvullend werden de clavicula en Pm lengte gemeten om de correlatie met de scapulothoracale spieren te bepalen.

Resultaten: In het algemeen vertoonde de scapula aan beide zijden een beweging volgens het normale patroon naar opwaartse rotatie en posterieure tilt. Opmerkelijk was een vermindere posterieure tilt van de AZ in vergelijking met de NAZ in het frontaal en sagittaal vlak. Interne/externe rotatie verschilde naargelang het vlak. De AZ vertoonde in elk vlak een licht verhoogde spieractiviteit van de MT en LT en een licht verlaagde activiteit van de UT in vergelijking met de NAZ.

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Een licht verlaagde activiteit van de SA aan de AZ kon geobserveerd worden in alle vlakken bij het heffen van de arm, dit in tegenstelling tot het laten zakken van de arm waarbij er een licht verhoogde activiteit waargenomen kon worden. In het frontaal vlak was de LT van de AZ significant meer actief dan de NAZ (p<0.05). Er werd een positieve correlatie (p<0.05) gevonden in de drie vlakken tussen de clavicula lengte van de AZ en de activiteit van de SA. Aan de NAZ daarentegen werd een negatieve correlatie gevonden tussen de lengte van de clavicula en de MT activiteit.

Conclusie: Uit deze resultaten kan geconcludeerd worden dat er geen bewijs is voor het verkiezen van een chirurgische behandeling boven een conservatieve ten aanzien van het herstellen van de scapulaire biomechanica. Verder onderzoek is nodig om de oorzaak van de minimale verschillen in onze studie te kunnen verklaren.

Sleutelwoorden: midshaft claviculafractuur – conservatieve behandeling – 3D scapulaire kinematica – EMG – scapulothoracale spieren
Introduction
Fractures

Injuries to the clavicle can include a sprain, separation, or dislocation of the clavicle joint or a fracture of the clavicle itself.\(^\text{(1)}\) Clavicular fractures are one of the most common skeletal injuries and account for 2-5% of all adult fractures.\(^\text{(2)}\) The curved bone is sensitive to fractures because of several reasons: (i) the subcutaneous and relatively anterior position, (ii) the exposure to transmitted forces, and (iii) the lack of muscle protection and poverty of strong ligaments.\(^\text{(2-4)}\)

Clavicle fractures have several classification systems, which determine the choice of treatment and help to predict the prognosis. The most widely used and accepted are the Allman classification and the Robinson classification.\(^\text{(5, 6)}\)

According to the Allman classification, clavicle fractures can be divided into three groups. Fractures of group I (midshaft fractures) occur on the middle third of the clavicle, fractures of group II on the lateral (distal) third and fractures of group III on the medial (proximal) third,\(^\text{(4)}\) accounting respectively for 80%, 15% and 5% of all clavicle fractures.\(^\text{(7)}\) The high percentage of midshaft fractures can be anatomically explained by the fact that the medial and lateral parts of the clavicle are secured by strong ligaments and muscles, while the middle part does not have strong attachments and is therefore more vulnerable to trauma.\(^\text{(8)}\)

When looking especially at the midshaft fractures in the Robinson classification, an update of the Edinburgh classification, two main types of fractures are defined: undisplaced (Type A) and displaced (Type B).\(^\text{(6)}\) A displaced fracture means that the bone is broken into two or more pieces which are not lined up straight,\(^\text{(9)}\) what occurs in more than half of the midshaft fractures.\(^\text{(10, 11)}\) The Robinson classification has been established as the most appropriate classification method for the midshaft fractures with the highest prognostic value for the treatment outcome in terms of union and non-union.\(^\text{(6, 9, 12)}\) Adults with a displaced fracture are more prone to develop non-union,\(^\text{(13)}\) a delayed indication for surgical intervention.\(^\text{(6, 12)}\)

Treatment

Different methods are used for managing clavicle fractures.\(^\text{(5-14)}\) In general, two groups can be defined: the operative and nonoperative method.\(^\text{(5)}\)
Surgery is often considered for open fractures, affected skin, neurological disorders, vascular injury, ipsilateral serial rib fractures, or floating shoulder.\(^2\, 14\) There are several surgical methods to treat a midshaft fracture: open or closed reduction with plate fixation, or intramedullary fixation, of which the titanium elastic nail is the most described option.\(^4\, 5\, 14\) The technique used depends on the characteristics of the patient and the fracture, as well as on the preference of the surgeon performing the operation.\(^3\, 5\)

Nonoperative treatment is the most regular method for undisplaced midshaft fractures and fractures with cortical alignment.\(^4\) The conservative treatment involves an immobilization with a broad arm sling or a figure-of-eight-bandage.\(^5\) Nowadays, there is no clear evidence of the best technique and duration of immobilization,\(^2\) furthermore no difference was found in the healing time or the union rate.\(^2\, 3\)

However, the occurrence of non-union is one of the most described complications\(^14\, 15\) as well as shortening of the clavicle which occurs in roughly half of the cases after conservative treatment.\(^16\, 17\)

In case of surgical treatment, there is a possibility of post-surgery complications (for example: migration of pins or wound infections) and re-operations.\(^18\)

When looking at functional outcomes, there is conflicting evidence. Some studies showed that operative treatment is associated with higher patient satisfaction and better Disability of the Arm, Shoulder and Hand Questionnaire (DASH) and Constant Shoulder (CS) scores.\(^19\, 20\) However, a more recent study by Woltz et al. (2017) found equal CS and DASH scores between the two treatments.\(^21\) It is now assumed that there are minimal differences in DASH and CS scores that are not perceived as clinically relevant by the patient.\(^15\) Furthermore, no difference in active and passive range of motion was found between both groups.\(^19\, 20\)

The functional outcomes are mainly the result of normal underlying shoulder biomechanics and of adequate scapulothoracic muscle activity. To reach full elevation, a normal scapulothoracic movement with simultaneous action of the sternoclavicular and acromioclavicular joint is required.\(^22\, 23\) In general, the scapula moves around three different axes (Figure 1): upward/downward rotation around a dorsal-ventral axis, anterior/posterior tilt around a latero-lateral axis and internal/external rotation around a longitudinal axis. During humeral elevation, the scapula shows a progressive pattern of upward rotation, posterior tilt and external rotation, together with clavicular elevation, retraction and posterior axial rotation.\(^24\, 25\)
To our knowledge, only one study examined shoulder biomechanics after a conservatively treated midshaft fracture without exclusion of non-shortened clavicles. Stegeman et al. (2015) found a slightly reduced posterior tilt, a slightly increased internal rotation and a slightly increased upward rotation during abduction and anteflexion compared to the healthy side. Further the study reported more internal rotation in rest. However, measurements were only made to arm movements up to 90°, missing the higher and more functional angles. Limitations in overhead elevation correlate with lower quality of life and inferior scores on functional questionnaires such as the Shoulder pain and disability index (SPADI) or DASH.

There is also a possibility that a fracture affects shoulder biomechanics indirectly by changing muscle activity or coordination. The three parts of the trapezius (upper trapezius (UT), middle trapezius (MT), lower trapezius (LT)) and the serratus anterior (SA) act as synergists to move and stabilize the scapula during elevation. Abnormal muscle work, muscle weakness in one or more of the components, or muscle imbalances are highly assumed to contribute to atypical scapular motion.

Up to now, there is a lack of information on whether a clavicle fracture would cause a difference in clavicle or pectoralis minor (Pm) length, a change in shoulder biomechanics or a modification in the function of the scapulothoracic muscles and what the impact would be.

Therefore, the aim of this study was threefold: to determine differences in (i) scapular motion and (ii) scapulothoracic muscle activity during active elevation in three different planes between the conservatively treated and healthy side of patients with a midshaft clavicle fracture and (iii) correlations were investigated between clavicle length or Pm length with scapulothoracic muscle activity.
We hypothesized that scapular kinematics and muscle activity of the scapular stabilizers would not alter between the two sides, which suggests that conservative treatment is an effective treatment option. Further, we expect to find a correlation between the clavicle or Pm length and the scapulothoracic muscles. If the clavicle or Pm length is shortened, it would influence the scapulothoracic muscles due to a more protracted shoulder position.
Methods

Participants

For this descriptive laboratory study, people with a previous clavicle fracture treated in UZ Ghent or AZ Sint-Jan Bruges in Belgium were recruited. The participants had to meet the following inclusion criteria: age between 18-60 years and a conservatively treated midshaft clavicle fracture at least one year after trauma. Patients were excluded if there was a neurological deficit of the upper limbs or in case of a refracture or dislocation. The following table (Table 1) shows the characteristics of the participants. Written informed consent of each participant was obtained before testing. This study was approved by the Ethical Committee of Ghent University (EC 2017-1029).

Table 1: Characteristics of the participants

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>n</th>
<th>Mean, ± SD, [min – max]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>19</td>
<td>(83%)</td>
</tr>
<tr>
<td>Female</td>
<td>4</td>
<td>(17%)</td>
</tr>
<tr>
<td>Age (yrs)</td>
<td></td>
<td>39.4 ± 11.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[19 – 60]</td>
</tr>
<tr>
<td>Height (m)</td>
<td></td>
<td>1.767 ± 0.0750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1.61 – 1.86]</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td>78.65 ± 14.910</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[52.0 – 109.6]</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td></td>
<td>25.004 ± 3.3738</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[20.06 – 33.09]</td>
</tr>
<tr>
<td>Fracture side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>10</td>
<td>(43%)</td>
</tr>
<tr>
<td>Left</td>
<td>13</td>
<td>(57%)</td>
</tr>
<tr>
<td>Dominant side</td>
<td>9</td>
<td>(39%)</td>
</tr>
<tr>
<td>Length of clavicle IS (mm)</td>
<td>152.91 ± 9.712</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[134.7 – 168.0]</td>
</tr>
<tr>
<td>Length of clavicle NIS (mm)</td>
<td>161.58 ± 11.623</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[141.4 – 180.9]</td>
</tr>
<tr>
<td>Length of Pm IS (mm)</td>
<td>144.71 ± 13.402</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[107.5 – 162.2]</td>
</tr>
<tr>
<td>Length of Pm NIS (mm)</td>
<td>149.37 ± 13.601</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[121.2 – 175.4]</td>
</tr>
</tbody>
</table>

BMI = Body Mass Index; IS = injured side; kg = kilogram; m = meter; mm = millimeter; n = number; NIS = non-injured side; Pm = pectoralis minor; SD = standard deviation; yrs = years
General study design

Electromyography (EMG) activity of four scapulothoracic muscles (UT, MT, LT and SA) at both sides was synchronously measured with the scapular three-dimensional (3D) kinematics during elevation in three planes (frontal/scapular/sagittal). Before the subject starts, a randomization between the planes was executed by drawing cards. Each subject performed five times an elevation in every plane with 30 seconds of rest between the several attempts. This was conducted for both sides separately starting with the non-injured side (NIS). The elevations were performed over five seconds, always executed using a metronome with a frequency of 60 beats per minute. Standardization was also provided using external feedback with a vertical bar placed in front of the arm to mark the plane and end of the elevation (120°). Between each plane and each side, three minutes of rest were taken. The measurements were performed in real time to ensure that a neutral spine is maintained, and the exercises and degrees of elevation are standardized.

Testing procedure

Clinical evaluation

Clinical measurements and evaluations were obtained from each subject prior to testing: Body Mass Index (BMI), length of the clavicle bilateral and length of the Pm on both sides. The length of the clavicle was measured using an electronic sliding vernier Hogetex Digital Caliper with 300 millimeter (mm) accuracy. A skin-level measurement executed by palpation of landmarks represented the Pm. According to the protocol of Borstad et al. (2005), the landmarks were the caudal edge of the fourth rib at the level of the sternum and the inferomedial aspect of the processus coracoideus. Both measurements were performed by the same researcher (KB) and repeated three times to minimize measurement errors. General inspection in stance was performed, to notice scapular dyskinesis or major deformities that may affect the measurements.

Skin preparation

Before EMG measurements, the skin was first shaved using a razor blade, then scrubbed with a cotton ball and scrub gel (Nuprep® skin prep gel, Weaver and Company, Unit B Aurora, Colorado) and finally cleaned with an alcohol cloth (Chem-lab NV, Zedelgem, Belgium) to reduce skin impedance. Surface electrodes (silver–silver chloride Ambu BlueSensor P [reference no. P-00-S/50], 40.8 34 mm; Ambu, Ballerup, Denmark) were placed in line with the muscle fiber orientation, with a one centimeter interelectrode distance at reference points described in accordance with the instructions of Basmajian et al. (1985).
The surface electrodes were connected to a direct transmission system ((Ultium) EMG sensor (Noraxon USA Inc)) with shielded cables. The cables were taped on the skin to avoid movement artefacts. The EMG data were collected by a Ultium Desk Receiver (Noraxon USA Inc) at a sampling rate of 2000 Hertz (Hz).

Maximal voluntary isometric contraction

The standardized warming-up of the shoulder girdle on both sides consisted of multidirectional shoulder movements: 15 repetitions of internal and external rotation against light resistance in a neutral position and in 90° shoulder abduction, followed by 20 repetitions of circulatory anteflexion.

After the warming-up, the following maximal voluntary isometric contractions (MVICs) were performed based on the protocol of Castelein et al. (2015): prone V, prone T, seated U and seated T. The testing positions are presented in Appendix 1. These tests were executed three times on both sides, beginning with the NIS, with 30 seconds of rest between each attempt. The contraction was held for five seconds. Between each testing position, the subject was given 90 seconds of rest. The resistance was always applied by the same investigator (KB) to increase reliability.

3D analysis and EMG measurement

After calibration of the field, reflective 12 mm markers were subsequently applied to bony references of the subject for the measurement of the 3D kinematic data (Table 2). Figure 2 shows the placement of EMG electrodes and the markers for 3D analysis, the latter based on the International Society of Biomechanics (ISB) guidelines. A marker capture frequency of 200 Hz was used to collect the kinematic data by eight motion capture cameras (six Oqus 31 and two Oqus 4). Each marker had to be visible by at least three cameras during the complete analysis.

Afterwards, the elevations on both sides were performed in the three different planes while both EMG activity of four scapulothoracic muscles (UT, MT, LT, SA) and 3D kinematics were collected synchronously using the Qualisys Track Manager (QTM) software (Qualisys Track Manager 2019.3, Qualisys AB, Sweden).
Table 2: 3D marker placement

<table>
<thead>
<tr>
<th>Segment</th>
<th>Placement of the marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>LFHD – RFHD – LBHD - RBHD</td>
</tr>
<tr>
<td>Thorax</td>
<td>C7 – T8 - IJ (deepest point) - Px (most caudal point on the sternum) - sternocostal joint 3 right side – sternocostal joint 4 left side</td>
</tr>
<tr>
<td>Scapula</td>
<td>TS – AI – AA - PC (most ventral point) – Z-Y-X cluster (angle of the acromion) – LAC - RAC</td>
</tr>
<tr>
<td>Humerus</td>
<td>Cluster of 4 markers on upper arm (PM-PL-DM-DL) - EL (most caudal point)- EM (most caudal point)</td>
</tr>
<tr>
<td>Lower arm</td>
<td>Cluster of 4 markers on lower arm (PM – PL – DM - DL) – RWA - RWB</td>
</tr>
<tr>
<td>Pelvis</td>
<td>LSIAS – RSIAS – LSIPS – RSIPS - centre of crista iliaca left and right</td>
</tr>
</tbody>
</table>

AA = angulus acromialis; AI = angulus inferior; DL = distal-lateral; DM = distal-medial; EL = epicondylus laterale; EM = epicondylus mediale; IJ = incisura jugularis; LAC = left acromioclavicular joint; LBHD = left back head; LFHD = left front head; LSIAS = left spina iliaca anterior superior; LSIPS = left spina iliaca posterior superior; PC = processus coracoideus; PL = proximal-lateral; PM = proximal-medial; Px = processus xiphoideus; RAC = right acromioclavicular joint; RBHD = right back head; RFHD = right front head; RSIAS = right spina iliaca anterior superior; RSIPS = right spina iliaca posterior superior; RWA = processus styloideus radii; RWB = processus styloideus ulnae; TS = trigonum spinae

Figure 2: 3D and EMG marker placement

Signal Processing and Data Analysis

For the signal processing of the 3D kinematic data, the data collected by the motion capture cameras was imported in Qualisys. All markers were digitally labelled throughout the entire arm elevation, ghost markers were deleted, and gaps were filled using a polynomial, linear or relational filling.
After this, a c3d file was formed which was imported in Visual 3D (v6.01.36, C-motion Inc., USA). Visual 3D was used to generate the numeric data of the 3D measurements as well as the EMG data. For the 3D scapular motions, the ‘Upper Limb Pelvis Model 2020’ was used to calculate the joint angles. This model works with an inverse kinematics constraint model based on ISB recommendations of Wu et al.\(^{(36)}\) Statistical Parametric Mapping (SPM) was applied for further processing of 3D scapular kinematics.

The MyoResearch 3.14 Master edition (Noraxon USA Inc) software was used for the signal processing of the raw EMG signals of the MVIC’s. First electrocardiogram reduction was performed by removing the cardiac artifacts from the raw EMG signals, followed by a bidirectional 30-Hz high-pass Butterworth filter, a full-wave rectification and smoothing (root mean square, 100 milliseconds window). A marker was manually placed three seconds before the maximum peak of each repetition of the EMG pattern. For all muscles, the average mean amplitude of the three attempts over the positions prone V, prone T, seated U and seated T was extracted. If there were outliers, defined as deviating 20% of the middle value, they were not included in the calculation of the mean EMG amplitude. To define the MVIC for each muscle, the highest mean value of the four different MVIC tests for that muscle was taken.

Visual 3D was also used to calculate the mean EMG activity of the UT, MT, LT and SA during elevation in the three planes. The EMG data were split in two window frames of five seconds: a concentric phase (CON); from the start of the movement to the point of maximal elevation, and an eccentric phase (ECC); from the point of maximal elevation to the end of the movement. The average EMG activity of the middle three trials was calculated, again without values deviating more than 20% of the middle value.

Afterwards, the EMG activity of each subject was normalized. The average EMG activity during the elevation task was divided by the MVIC for that muscle and expressed as a percentage, making it possible to compare the participants. Normalization was also implemented for the length of the Pm and the clavicle. The normalization of the Pm was performed according to the pectoralis minor index (PMI) of Borstad et al. (2005): dividing the length of the Pm by the body length of the person and multiplying it by 100.\(^{(33)}\) The same formula was used for normalization of the clavicle length, but this method has not been validated in literature.
Statistical analysis

The descriptives were analyzed using IBM SPSS Statistics for Windows Version 27.0 (IBM Corp. Armonk, NY: IBM Corp). For each condition (frontal, scapular or sagittal) and each phase (ECC or CON), a determination was made whether the EMG values of each muscle were normally distributed or not, using the Shapiro-Wilk test and histograms. In case of a normal distribution, a parametric analysis was performed, using a paired sample t-test. If the values were not normally distributed, the non-parametric Wilcoxon test was applied. The level of statistical significance was a priori defined as p<0.05.

The correlations between the clavicle length or Pm length and scapulothoracic muscle activity were statistically evaluated using Pearson correlation tests. To determine the significance (p<0.05) IBM SPSS Statistics 27.0 was used.

To compare the 3D scapular kinematics between the injured side (IS) and NIS, a curve analysis was executed using SPM. To achieve the SPM analysis, all data were exported to Matlab (Matlab R2016b (9.1.0.441655), The Mathworks Inc, Natrick, MA). The data were normalized over time to 101 data frames. This approach allows an analysis of the mean joint angle during the entire kinematic movement on 101 data frames instead of an analysis based on one or a few points.\(^{[37]}\) SPM is a statistical method based on the Random Field Theory.\(^{[37, 38]}\)

Specifically, a SPM paired t-test (SPM\(\{t\}\)) was executed with \(\alpha=0.05\) to compare scapular kinematics between both groups. The SPM\(\{t\}\) trajectory was calculated from the mean joint angles at 101 points in the three different planes. The temporal smoothness was then estimated and finally, the critical threshold SPM\(\{t\}\) was calculated. The null hypothesis expected a significant difference between the IS and the NIS. This null hypothesis was rejected if the SPM\(\{t\}\) trajectory exceeded the critical threshold. All statistical analyses of this study were performed using the open source spm1d code (www.spm1d.org) in Matlab.
Results

A total of 28 participants were recruited for this study. Although, one person was later identified as fulfilling the exclusion criteria. Furthermore, there were four dropouts of which three due to no show and one because of a technical defect. The final analysis was completed on 23 participants.

Scapular 3D kinematics

In general, no significant difference was found in the kinematics of the shoulder between the IS and NIS in any plane.

Frontal plane

During analysis in the frontal plane, the scapula stands in a relative internal rotation, a slightly upward rotation and an anterior tilt at the beginning and the end of the movement. This anterior tilt was more pronounced on the IS compared to the NIS and the internal rotation position was greater on the NIS. Both sides showed the same movement pattern during elevation: external rotation (Figure 3), upward rotation (Figure 4) and posterior tilt (Figure 5). A greater movement towards external rotation can be observed on the IS compared to the NIS (Figure 3). The opposite was seen in the posterior tilt, which was more pronounced in the NIS (Figure 5).

![Figure 3](image)

**Figure 3:** a) Mean trajectories for internal (negative degrees)/external (positive degrees) rotation during elevation in the frontal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 2.998 (red dashed line) was not exceeded.
Figure 4: a) Mean trajectories for upward (positive degrees)/downward (negative degrees) rotation during elevation in the frontal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.146 (red dashed line) was not exceeded.

Figure 5: a) Mean trajectories for anterior (negative degrees)/posterior (positive degrees) tilt during elevation in the frontal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.064 (red dashed line) was not exceeded.
**Scapular plane**

In the scapular plane, the same position of the scapula can be noticed at the beginning and end of the elevation as in the frontal plane. Both sides showed the same pattern to posterior tilt (Figure 8) and upward rotation (Figure 7). Considering the internal/external rotation (Figure 6), a different pattern of the IS compared to the NIS can be seen. The NIS moved towards internal rotation during elevation while the IS moved very slightly to external rotation.

![Scapular plane - Internal/External rotation](image1)

![Paired t-test](image2)

**Figure 6:** a) Mean trajectories for internal (negative degrees)/external (positive degrees) rotation during elevation in the scapular plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 2.974 (red dashed line) was not exceeded.
Figure 7: a) Mean trajectories for upward (positive degrees)/downward (negative degrees) rotation during elevation in the scapular plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.147 (red dashed line) was not exceeded.

Figure 8: a) Mean trajectories for anterior (negative degrees)/posterior (positive degrees) tilt during elevation in the scapular plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.173 (red dashed line) was not exceeded.

Sagittal plane

The scapula was positioned in an internal rotation, an anterior tilt and a slight upward rotation at the beginning and end of the elevation in the sagittal plane. Both sides followed the same pattern to internal rotation (Figure 9), upward rotation (Figure 10) and a slightly anterior tilt (Figure 11) during the elevation. A more pronounced movement to anterior tilt can be observed on the IS.
Figure 9: a) Mean trajectories for internal (negative degrees)/external (positive degrees) rotation during elevation in the sagittal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 2.977 (red dashed line) was not exceeded.

Figure 10: a) Mean trajectories for upward (positive degrees)/downward (negative degrees) rotation during elevation in the sagittal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.077 (red dashed line) was not exceeded.
Figure 11: a) Mean trajectories for anterior (negative degrees)/posterior (positive degrees) tilt during elevation in the sagittal plane injured side (black) and non-injured side (red). b) The paired t-test statistic SPM (t). The critical threshold of 3.143 (red dashed line) was not exceeded.

**EMG activity**

An overview of the descriptive statistics of the paired sample t-test is shown in Table 3 - 5. In general, following results can be observed: a slightly increased activity of the MT and LT on the IS compared to the NIS in all three planes and a slightly decreased activity of the UT on the IS in the three planes. During the CON phase of the movement, the IS showed a generalized slightly reduced activity of the SA compared to the NIS. This in contrast to the ECC phase, where a general slightly increased activity of the SA can be observed on the IS in all planes.

A significant difference in activity of the LT was found in the frontal plane between the IS and NIS, in both the CON (p<0.05) and ECC phase (p<0.01). In both cases, the LT was more active in the IS compared to NIS. For the CON phase, a mean activity of 12.29% for the IS versus 9.39% for the NIS was found and respectively 8.66% versus 6.52% in the ECC phase. No statistically significant results were found for the EMG activity of the scapulothoracic muscles in the other two planes (scapular and sagittal).
Table 3: Descriptive statistics for EMG activity during elevation in the frontal plane

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[9.77-19.33]</td>
<td>[15.44-25.85]</td>
<td>[8.64-14.83]</td>
<td>[8.26-16.32]</td>
<td>[6.03-11.28]</td>
<td>[8.78-14.07]</td>
</tr>
<tr>
<td>NIS</td>
<td>UT</td>
<td>CON</td>
<td>15.77 ± 12.64</td>
<td>17.40 ± 11.42</td>
<td>9.39 ± 6.94</td>
<td>6.53 ± 4.27</td>
<td>19.28 ± 14.89</td>
<td>10.98 ± 7.66</td>
</tr>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[10.30-21.24]</td>
<td>[12.34-22.46]</td>
<td>[7.44-12.58]</td>
<td>[6.39-12.40]</td>
<td>[4.68-8.37]</td>
<td>[7.66-14.29]</td>
</tr>
</tbody>
</table>

P-value (AS with NAS) .910

Mean, ± SD, [95% CI]; CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; UT = upper trapezius; * = significant (p<0.05)

Table 4: Descriptive statistics for EMG activity during elevation in the scapular plane

<table>
<thead>
<tr>
<th>IS</th>
<th>UT</th>
<th>CON</th>
<th>13.53 ± 8.30</th>
<th>12.56 ± 11.24</th>
<th>8.43 ± 6.82</th>
<th>18.83 ± 11.16</th>
<th>12.54 ± 7.45</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[9.86-17.21]</td>
<td>[7.44-17.68]</td>
<td>[5.33-11.53]</td>
<td>[13.75-23.91]</td>
<td>[9.15-15.93]</td>
</tr>
<tr>
<td>NIS</td>
<td>UT</td>
<td>CON</td>
<td>12.24 ± 7.18</td>
<td>10.45 ± 7.18</td>
<td>6.91 ± 4.62</td>
<td>20.91 ± 15.83</td>
<td>11.54 ± 7.79</td>
</tr>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[9.85-14.64]</td>
<td>[7.35-13.56]</td>
<td>[4.91-8.91]</td>
<td>[14.07-27.76]</td>
<td>[8.17-14.91]</td>
</tr>
</tbody>
</table>

P-value (AS with NAS) .394

Mean, ± SD, [95% CI]; CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; UT = upper trapezius; * = significant (p<0.05)

Table 5: Descriptive statistics for EMG activity during elevation in the sagittal plane

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[2.78 - 6.81]</td>
<td>[6.64 - 17.88]</td>
<td>[4.49-10.25]</td>
<td>[14.68-26.08]</td>
<td>[9.82-17.34]</td>
</tr>
<tr>
<td>NIS</td>
<td>UT</td>
<td>CON</td>
<td>5.77 ± 1.36</td>
<td>9.89 ± 6.27</td>
<td>6.41 ± 3.72</td>
<td>22.15 ± 15.24</td>
<td>13.33 ± 8.80</td>
</tr>
<tr>
<td></td>
<td>ECC</td>
<td>CON</td>
<td>[4.15 - 7.40]</td>
<td>[7.11-12.67]</td>
<td>[4.76-8.06]</td>
<td>[15.39-28.91]</td>
<td>[9.42-17.23]</td>
</tr>
</tbody>
</table>

P-value (AS with NAS) .291

Mean, ± SD, [95% CI]; CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; UT = upper trapezius; * = significant (p<0.05)
Correlation clavicle and EMG

Table 1 with the characteristics of the participants shows that the mean length of the clavicle at the IS (152.91 ± 9.71) is lower than the NIS (161.58 ± 11.62). The following tables (Table 7 – 9) are reporting the results concerning the correlation between clavicle length and the EMG activity of each muscle in the three different planes on the IS and NIS. A strength of correlation was attributed considering the ranges shown in Table 6.\(^{(39)}\)

**Table 6: Strength of correlation**

<table>
<thead>
<tr>
<th>Strength of correlation</th>
<th>Positive correlation</th>
<th>Negative correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.1 to 0.3</td>
<td>-0.1 to -0.3</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.3 to 0.5</td>
<td>-0.3 to -0.5</td>
</tr>
<tr>
<td>Strong</td>
<td>0.5 to 1.0</td>
<td>-0.5 to -1.0</td>
</tr>
</tbody>
</table>

In the frontal and sagittal plane, a negative moderate correlation was noted between the MT activity of the NIS and the clavicle length. Additionally, a negative strong correlation of the MT was found in the scapular plane which was significant. Also, the SA of the IS showed a significant positive strong correlation in every plane. In addition, a significant negative moderate correlation was noted between the LT of the NIS in the ECC phase of the elevation in the frontal plane and the length of the clavicle. The other values can be defined as low correlations.

**Table 7: Results Pearson test for the correlation between clavicle length and EMG activity during elevation in the frontal plane**

<table>
<thead>
<tr>
<th></th>
<th>UT</th>
<th></th>
<th>MT</th>
<th></th>
<th>LT</th>
<th></th>
<th>SA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson</td>
<td>p-value</td>
<td>Pearson</td>
<td>p-value</td>
<td>Pearson</td>
<td>p-value</td>
<td>Pearson</td>
<td>p-value</td>
</tr>
<tr>
<td>CON</td>
<td>IS</td>
<td>-.078</td>
<td>.732</td>
<td>-.083</td>
<td>.712</td>
<td>-.069</td>
<td>.760</td>
<td>.589*</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>-.078</td>
<td>.723</td>
<td>-.365</td>
<td>.095</td>
<td>-.275</td>
<td>.203</td>
<td>.140</td>
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<tr>
<td>ECC</td>
<td>IS</td>
<td>-.195</td>
<td>.385</td>
<td>-.105</td>
<td>.641</td>
<td>-.012</td>
<td>.959</td>
<td>.508*</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>-.080</td>
<td>.717</td>
<td>-.401</td>
<td>.058</td>
<td>-.424*</td>
<td>.044*</td>
<td>.111</td>
</tr>
</tbody>
</table>

CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; SA = serratus anterior; UT = upper trapezius; * = significant (p<0.05)
Correlation Pm and EMG

As shown in Table 1, the average Pm length of the IS (144.71 ± 13.40) is shorter than the NIS (149.37 ± 13.60). Additionally, the correlation between the Pm length and EMG activity of the four muscles was analyzed. These results are listed in Table 10 – 12.

A significant negative moderate correlation was observed between the Pm and the LT activity of the NIS during the ECC phase of elevation in the frontal plane. Also, a moderate correlation was found during the CON phase but this was not significant. Considering elevation in the sagittal plane, the UT of the NIS showed a significant positive moderate correlation during the CON phase. During the ECC phase, a significant positive strong correlation was found. Additionally, a negative moderate correlation can be observed in the ECC phase of the MT on the NIS. The remaining correlations had a low strength.
**Table 10:** Results Pearson test for the correlation between Pm length and EMG activity during elevation in the frontal plane

<table>
<thead>
<tr>
<th></th>
<th>UT Pearson p-value</th>
<th>MT Pearson p-value</th>
<th>LT Pearson p-value</th>
<th>SA Pearson p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>IS</td>
<td>.067</td>
<td>.767</td>
<td>-.192</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.190</td>
<td>.385</td>
<td>-.115</td>
</tr>
<tr>
<td>ECC</td>
<td>IS</td>
<td>.066</td>
<td>.772</td>
<td>-.078</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.207</td>
<td>.344</td>
<td>-.172</td>
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</table>

CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; SA = serratus anterior; UT = upper trapezius; * = significant (p<0.05)

**Table 11:** Results Pearson test for the correlation between Pm length and EMG activity during elevation in the scapular plane

<table>
<thead>
<tr>
<th></th>
<th>UT Pearson p-value</th>
<th>MT Pearson p-value</th>
<th>LT Pearson p-value</th>
<th>SA Pearson p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>IS</td>
<td>.003</td>
<td>.990</td>
<td>-.157</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.196</td>
<td>-.157</td>
<td>-.279</td>
</tr>
<tr>
<td>ECC</td>
<td>IS</td>
<td>.038</td>
<td>.869</td>
<td>-.138</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.287</td>
<td>.184</td>
<td>-.275</td>
</tr>
</tbody>
</table>

CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; SA = serratus anterior; UT = upper trapezius; * = significant (p<0.05)

**Table 12:** Results Pearson test for the correlation between Pm length and EMG activity during elevation in the sagittal plane

<table>
<thead>
<tr>
<th></th>
<th>UT Pearson p-value</th>
<th>MT Pearson p-value</th>
<th>LT Pearson p-value</th>
<th>SA Pearson p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>IS</td>
<td>-.035</td>
<td>.877</td>
<td>-.122</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.489*</td>
<td>.021*</td>
<td>-.217</td>
</tr>
<tr>
<td>ECC</td>
<td>IS</td>
<td>-.015</td>
<td>.948</td>
<td>-.052</td>
</tr>
<tr>
<td></td>
<td>NIS</td>
<td>.550*</td>
<td>.008*</td>
<td>-.414</td>
</tr>
</tbody>
</table>

CON = concentric phase; ECC = eccentric phase; IS = injured side; LT = lower trapezius; MT = middle trapezius; NIS = non-injured side; SA = serratus anterior; UT = upper trapezius; * = significant (p<0.05)
Discussion

Interpretation of results

The purpose of this study was to investigate if a conservatively treated midshaft clavicle fracture would alter 3D scapular kinematics and/or scapulothoracic muscle activity, compared to the healthy side.

Scapular biomechanics

In general, the scapular motion on the IS and NIS showed the normal pattern of progressive upward rotation and posterior tilt. Internal/external rotation differed depending on the plane of elevation.²⁴, ⁴⁰ Although scapular external rotation is an accepted component during elevation, minimal external rotation in the scapular plane and even an internal rotation in the sagittal plane were observed during elevation in healthy athletes.⁴¹ The athletic population also showed more posterior tilt in the frontal plane compared to the scapular and sagittal plane.⁴¹ Identical patterns of internal/external rotation and a similar amount of posterior tilt can be found in our results, which indicates that the general scapular motion pattern of patients with a midshaft clavicular fracture is normal in the different planes.

No significant difference was found between the IS and NIS and both trajectory lines follow nearly the same motion pattern, except in the scapular plane. The IS moved slightly towards external rotation, while the NIS shifted towards internal rotation. Similar results were also found in patients with non-union clavicular fractures in the study of Kim et al. (2017).⁴² Also, the findings of Kim et al. (2017) are in line with our results, as no significant differences between IS and NIS were found.⁴² Based on those results, a clavicular fracture seems to have no effect on scapular biomechanics.

A striking trend in the results was the decreased posterior tilt of the IS compared to the NIS in the frontal and sagittal plane. A possible explanation could be that a shorter clavicle on the IS resulted in a more anterior tilted position. The decreased posterior tilt was also one of the findings in the participants with nonoperatively treated clavicular fractures in the study of Stegeman et al. (2015).²⁶ Also, an increased internal and upward rotation on the IS during elevation up to 90° were noted.²⁶ The last mentioned components vary from our results, which can partially be explained by the remarkable difference in testing protocol. The participants of Stegeman et al. (2015) were tested in a sitting position and performed the elevation bilateral.²⁶ A previous study showed a slight significant difference of 1.8° upward rotation between standing and neutral sitting position.⁴³ In addition, unilateral elevation showed more external rotation compared to bilateral elevation.⁴⁴
It should be noted that there is limited research in differences between sitting and standing position and between unilateral and bilateral elevation. This suggests that the difference in test position may not be the only reason that the results differ.

An additional explanation can be that more than half of the patients in the study of Stegeman et al. (2015) reported irritation, pain, or fatigue during (prolonged) elevation. Our participants did not have residual complaints. In a study that compared patients diagnosed with hypermobile Ehler-Danlos syndrome with multidirectional shoulder laxity, the patients with Ehler-Danlos showed decreased upward rotation and posterior tilt, while persons with multidirectional shoulder laxity equaled the healthy control group. As Ehler-Danlos is a symptomatic condition, in contrast to multidirectional shoulder laxity, the authors suggest that the altered scapular motion can be a consequence of pain. As such, scapular dyskinesis may appear as an antalgic movement pattern. Because most of the participants of Stegeman et al. (2015) complained about pain, there is a chance that they recruited more people with an antalgic scapular motion pattern.

Nevertheless, the scapular alterations in the three planes in the study of Stegeman et al. (2015) were small and not perceived as functionally relevant.

**EMG activity**

In general, a slightly increased activity of the MT and LT of the IS compared to the NIS and a slightly decreased activity of the UT of the IS in all three planes can be observed. Most shoulder pathologies demonstrate the opposite pattern: increased UT activity and decreased MT and LT activity. For example, studies with a similar study protocol but in a population with scapular dyskinesis, showed more UT and less LT activity than the control group. Also, exercise therapy implemented after shoulder injury commonly emphasizes LT and SA activation and UT reduction. Although, patients diagnosed with hypermobile Ehler-Danlos syndrome or hypermobile spectrum disorder showed significantly higher MT, infraspinatus and deltoid muscle activity, supporting scapulothoracic and glenohumeral stability.

Two plausible hypotheses can be suggested for these results. First, Hart et al. (2010) reported the phenomenon of arthrogenic muscle inhibition of the quadriceps after knee surgery. Arthrogenic muscle inhibition is an unconscious response of the body to a joint injury, in which the neural innervation to the surrounding muscles is inhibited as a protective mechanism. The inhibition could also be determined by pain and disuse.
Relating to the scapulothoracic muscles, an injury such as a midshaft fracture may lead to an arthrogenic muscle inhibition of the UT, considering its attachment near the lateral part of the clavicle. Despite the scapulohumeral joint would keep its stability, the MT and LT can overcompensate.

A second possible explanation can be found on the fact that the most common complications of clavicle fractures are malunion, angulation or shortening of the clavicle after healing. These frequently occurring complications have an important influence on the anatomical geometry and on the muscle moment of the muscles that work directly or indirectly over the clavicle.

Furthermore, a significant difference in activity of the LT was found in the frontal plane between the IS and NIS, in both the CON and ECC phase of the movement. In both cases, the LT was more active in the IS compared to the NIS. A possible explanation can be found when observing the scapular 3D kinematics. The scapula of the IS stands more in anterior tilt both at the onset and the end of elevation compared to the NIS, most pronounced in the frontal plane. To compensate for this anterior tilt, the LT could be more active, whose inferomedial directed muscle fibers could also contribute to posterior tilt of the scapula during elevation of the arm.

Lastly, during the CON phase of the movement, the IS showed a generalized slightly reduced activity of the SA compared to the NIS. The SA behaves as the main stabilizer of the scapula on the thorax and functions as a synergist of the Pm contributing to the protraction of the scapula. Considering the shortening of the mean values of the Pm length after a midshaft fracture in our study, it can be argued that the shoulder is already in a protraction position, thus less activity will be required.

Correlation clavicle and EMG

Results of the correlation must be interpreted as follows: a positive correlation means that when the clavicle shortens/lengthens, the scapulothoracic muscle activity respectively decreases/increases and vice versa for a negative correlation. A positive strong correlation was found between the length of the clavicle of the IS and the activity of the SA on the same side, in the three planes. These findings can be explained by a strictly structural explanation. Because of the shortening of the clavicle, the scapula is in more internal rotation, which contributes to less pretension of the SA.
At the NIS, a negative correlation was found between the MT and the clavicle length in the three planes. According to the article by Hillen et al. (2016), the maximum internal rotation moment decreases by 32% with a shortening of the clavicle. At the NIS, there was a relative lengthening of the clavicle compared to the IS, which results in less internal rotation of the scapula what triggers less pretension of the MT.

Correlation Pm and EMG

A shortened Pm can be identified at the IS in our results. The relatively short Pm could demonstrate adaptations such as loss of sarcomeres in series, increased proportions of connective tissue and loss of passive range of motion. According to Borstad et al. (2005), an adaptively short Pm can affect scapular kinematics and is therefore a potential mechanism for subacromial impingement.

A positive correlation was found between the UT and the Pm length during both phases on the NIS. This is in contradiction with the existing literature, where there is evidence for decreased SA and increased UT activity in patient populations identified with a shortened resting length of the Pm, tight posterior shoulder, thoracic kyphosis, or with flexed thoracic postures.

Strengths and limitations

A major strength of this study was the synchronous measurement of EMG activity and scapula 3D kinematics, providing a better knowledge of scapular motion during elevation. No other studies measured 3D kinematics and scapulothoracic muscle activity simultaneously in persons with a midshaft clavicle fracture. In addition, the use of SPM, a novel statistical assessment measure, allowed the determination of scapular position during the entire elevation. Finally, working with a metronome and external feedback with a vertical bar that indicated the correct plane and end degree of elevation resulted in a high grade of standardization.

However, some limitations had to be taken into account. The clavicle length was normalized using the body length, although this method has not been validated yet. In literature, the clavicle length is generally standardized to the length of the 12th rib but this information was not collected during the test moment. In the future, the clavicle length can be measured by medical imaging instead of bony palpation through the skin. The use of a CT scan would allow to consider the curved shape of the clavicle in the length measurement and to measure the axial rotation of the bone. Also, navigation ultrasound has proven to be a reliable, accurate and valid method.

A second limitation is that although cardiac artefacts were removed in Myoresearch, this could not be done in Visual 3D. Nevertheless, the cables were folded and well taped to the skin to prevent artefacts.
Another limitation is the fact that no maximum time limit was defined between the occurrence of the fracture and the test moment. A recent trauma could give different results between IS and NIS in terms of muscle activity and scapular 3D kinematics.

Finally, through the use of the PMI described by Borstad et al. (2005), a strong attempt was made to minimize the possibility of bias during measurement of the resting length of the Pm. Although this method has been validated using cadavers, there is no separate reliability analysis in human subjects. The in vivo Pm length measurement remains an indirect measurement. Moreover, the method of Borstad et al. (2005) assumes that the thorax is a rigid segment. Motion of the ribs relative to the sternum may cause small errors in the measurement of the Pm length.

Clinical relevance

Considering the results of this study, some clinical recommendations can be made towards the content of the treatment of patients with a midshaft clavicle fracture.

(1) Given the larger anterior tilt position from the start and a decreased posterior tilt during elevation on the IS, therapy should focus on a better scapular position in rest and during elevation. However, this more anterior tilted position could be a consequence of a shortened clavicle. In that case, the position is a structural deficit where posture exercises or restoring muscle balance (LT/SA) will not improve scapular stance.

(2) Since we found lower UT and higher MT and LT activity, specific exercises to restore intra-muscular muscle balance seems not necessary.

(3) A shorter clavicle is correlated with a weaker SA. Exercise therapy should target the SA of the IS to restore the optimal pretension position in rest.
Conclusion

The 3D scapular analysis during elevation in the three planes in shoulders with a healed midshaft fracture differs from those in none injured shoulders. These changes are small, do not result in clinically relevant changes in outcome and do not relate to the amount of clavicular or Pm shortening. The scapulothoracic muscles have developed an adaptive pattern to compensate the minimal scapular alteration. These results prove that there is no reason to choose surgical treatment over conservative treatment to restore the scapular biomechanics. Future research is needed to compare conservative treatment with operative intervention in order to detect the cause of the minimal differences in our results.
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Abstract in lekentaal

Context: Een sleutelbeenbreuk komt vaak voor. De behandeling kan operatief of conservatief gebeuren, al is nog niet duidelijk wat de beste optie is naar functionele uitkomst (beweeglijkheid, pijn, ...). Voor een goede functionele uitkomst zijn een normale onderliggende spierwerking en beweging van het schouderblad, waar het sleutelbeen mee verbonden is, noodzakelijk.

Doel: Deze studie onderzocht de onderliggende schouderbladbewegingen en spieractiviteit bij mensen met een conservatief behandelde sleutelbeenbreuk en vergeleek de aangedane zijde (AZ) met de niet-aangedane zijde (NAZ).

Methode: Spieractiviteit van vier spieren werd gemeten via kleefelektroden. Gelijktijdig werden de bewegingen van het schouderblad geregistreerd met 3D markers. De proefpersonen werd gevraagd de arm te heffen tot 120° in het vlak naast zich, voor zich en ertussen. Ook de lengte van het sleutelbeen en de spier pectoralis minor werd opgemeten. Telkens werd de AZ vergeleken met de NAZ.

Resultaten: Er was significant verhoogde activiteit van één spier tijdens het heffen van de arm in het vlak naast zich. Het schouderblad maakte de correcte beweging. Het sleutelbeen en de spier pectoralis minor die gemeten werden, waren korter aan de AZ.

Conclusie: Een conservatief behandelde sleutelbeenbreuk heeft een beperkte invloed op de spieractiviteit en schouderbladbewegingen. Een conservatieve behandeling lijkt een goede behandelmethode, maar verder onderzoek is nodig om de oorzaak van de minimale verschillen in deze studie te verklaren.

Kernwoorden: Sleutelbeenbreuk – conservatieve behandeling – spieractiviteit – beweging schouderblad – pectoralis minor
Bewijs van indiening bij het ethisch comité

**Afz.:** Commissie voor Medische Ethiek

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**Ons kenmerk**
BC-00020 596

**Uw kenmerk**
NV

**datum**
03/06/2020

**pagina**
1/2

**B.U.N.:** B6702020000183

*Adviesaanvraagformulier dd. 27/4/2020 (Document E) (Volledig ontvangen dd 29/04/2020)*
*Begeleidende brief dd.27/4/2020*
*Informatie- en waarschuwingennota getekend door Julie Stevens dd. 20/3/2020*
*Diverse: Alle geëigende documenten cfr. project BC-00020*

**Advis werd gevraagd door:** Prof. dr. Alexander Van Tonge

**BOVENVERMELDE DOCUMENTEN WERDEN DOOR HET ETHISCH COMITE BEOORDEELE. ER WERD EEN POSITIEF ADVIES GEGEVEN OVER DIT PROTOCOL OP 03/06/20, VEROVERT HET ADVIES EN MOET HET PROJECT TERUG INGEDEMD WORDEN.**

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All members of the Ethics Committee have reviewed this project. (The list of the members is enclosed.)
Betreft:
Advis voor monocentrische studie met als titel:
Titel hoofdstuk: "Klinische, radiologische en 3D analyse van conservatief behandeld claviculafracturen.
Titel thesis: Klinische, radiologische en 3D analyse van conservatief behandelde claviculafracturen. - Scriptie: Kaat Stepmann

B.I.U.M.: B6702020000184
*Adviesaanvraagformulier dd. 27/4/2020 (Document E) (Volledig ontvangen dd 28/04/2020)
*Begeleidende brief dd.27/4/2020
*Informatie- en waarschuwingsnota geleverd door Kaat Stepmann dd.28/3/2020
*Diverse: (Alle goedkeuringsdocumenten cfr. project BC-00020)

Advis werd gevraagd door: Prof. dr. Alexander Van Tongel

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Ons kenmerk Uw kenmerk datum pagina
BC-00020 E06 NVT 03/06/2020 1/2

Betreft: Advies voor monocentrische studie met als titel:
Titel hoofdstudie: "Klinische, radiologische en 3D analyse van conservatief behandelede claviculafracturen."
Titel thesis: "Klinische, radiologische en 3D analyse van conservatief behandelede claviculafracturen. - Scriptie: Lara Smis"

B.I.M.: B670232020000185

*Adviesaanvraagformulier dd. 27/4/2020 (Document E) (Volledig ontvangen dd 28/04/2020)
*Begeleidingsbrief dd. 27/4/2020
*Informatie- en waarschuwingstaal getekend door Lara Smis dd. 26/5/2020
*Diverse: (Alle goedgekeurde documenten cfr. project BC-00020)

Advies werd gevraagd door: Prof. dr. Alexander Van Tongel

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### Appendix

**Appendix 1: MVIC testing procedures according to Castelein et al. (2015)[25]**

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<thead>
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<th>Exercise</th>
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<tbody>
<tr>
<td><strong>Seated T</strong></td>
<td>Shoulder abducted to 90° (elbow fully extended) as resistance is applied above the elbow, in a downward direction (to resist abduction)</td>
</tr>
<tr>
<td><strong>Seated U (135°)</strong></td>
<td>Shoulder flexed to 135° (elbow fully extended) as resistance is applied above the elbow against further arm raise</td>
</tr>
<tr>
<td><strong>Prone T – thumbs up</strong></td>
<td>Shoulder horizontally abducted and externally rotated (elbow fully extended) as the examiner applies manual pressure downward (above the elbow) to resist adduction of the scapula and extension of the shoulder</td>
</tr>
<tr>
<td><strong>Prone V – thumbs up</strong></td>
<td>Arm raised above head in line with lower trapezius muscle fibers (elbow fully extended) as resistance applied above the elbow against further arm raise</td>
</tr>
</tbody>
</table>