EXTENDED REPORTS

Measurement of three dimensional shoulder movement patterns with an electromagnetic tracking device in patients with a frozen shoulder

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Objective: To compare three dimensional movement patterns of the affected and non-affected shoulder in patients with a frozen shoulder before and after physical therapy.

Methods: Patients with a unilateral frozen shoulder were assessed before and after three months of treatment. Three dimensional movement analysis was performed with the "Flock of Birds" electromagnetic tracking device while the patient raised their arms in three directions. Slopes of the regression lines of glenohumeral joint rotation versus scapular rotation, reflecting the scapulohumeral rhythm, were calculated. All assessments were made for both the affected and the unaffected side. Additional assessments included conventional range of motion (ROM) measurements and visual analogue scales (VAS) (0–100 mm) for shoulder pain at rest, during movement, and at night.

Results: Ten patients with a unilateral frozen shoulder were included. The slopes of the curves of the forward flexion, scapular abduction, and abduction in the frontal plane of the affected and the unaffected side were significantly different in all three movement directions. Mean differences were 0.267, 0.215, and 0.464 (all p values <0.005), respectively. Mean changes of the slopes of the affected side after treatment were 0.063 (p=0.202), 0.048 (p=0.169), and 0.264 (p=0.008) in forward flexion, scapular abduction, and abduction in the frontal plane, respectively. All patients showed significant improvement in active ROM (all p<0.005), and the VAS for pain during movement and pain at night (p<0.05).

Conclusions: With a three dimensional electromagnetic tracking system the abnormal movement pattern of a frozen shoulder, characterised by the relatively early laterorotation of the scapula in relation to glenohumeral rotation during shoulder elevation, can be described and quantified. Moreover, the system is sufficiently sensitive to detect clinical improvements. Its value in other shoulder disorders remains to be established.

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Measuring the range of motion (ROM) of the shoulder joint is important in the diagnostic and therapeutic approach to patients with shoulder disorders. Clinical assessments of joint ROM usually concern measurements made in one or two dimensions. The shoulder joint is, however, a complicated structure involving a number of motion segments, which move in relation to each other in various planes. Therefore, motion analysis of the shoulder joint requires a system that can measure movements in three dimensions. The ability of modern motion sensing technologies (cinematic, radiographic, and optical techniques) to describe three dimensional shoulder movement patterns is limited. In particular, the registration of movement of the scapula is difficult as it is not accessible by external markers because it moves under the skin along the thoracic wall while the humerus elevates.[1]

Recently, three dimensional electromagnetic tracking systems have become available which can measure lumbar spine,[2] cervical spine, and shoulder ROM[3] in healthy subjects. Earlier investigations with healthy volunteers showed good intersubject, interobserver, and day to day reliability.[3–6] Except for previous studies in patients with stroke and shoulder disorders,[7 8] three dimensional analysis of movement patterns with electromagnetic tracking systems in subjects with pain and movement limitations of the shoulder, such as patients with a frozen shoulder, has not yet been performed.

A frozen shoulder (adhesive capsulitis) is a disorder that is, apart from pain, characterised by a distinctive movement pattern of limited external rotation, abduction, forward flexion,

and internal rotation. It has a prevalence of 2–3% in the general adult population. While glenohumeral movement is decreased, the scapula moves earlier and faster in laterorotation in comparison with the movement pattern of unaffected shoulders. At physical examination this abnormal rhythm can be seen and palpated during the movement of the humerus in forward flexion or abduction. It is, however, difficult to describe and measure this abnormal movement pattern.

This study aimed at describing the movement pattern of the frozen shoulder with a three dimensional electromagnetic tracking device. A comparison between the movement patterns of the affected and unaffected side and between the movement patterns of the affected side before and after three months of physical therapy was made.

PATIENTS AND METHODS
Patients
Ten consecutive patients with a clinical diagnosis of a unilateral frozen shoulder participated in the study. They were all outpatients of the orthopaedic department of the Leiden University Medical Centre. A frozen shoulder was defined as a primary shoulder disorder with a pattern of limited joint mobility in abduction, forward flexion, and external rotation (passive range of motion <50% of the ROM of the unaffected

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Abbreviations: ROM, range of movement; VAS, visual analogue scale

side) and a joint capacity of <15 ml as determined by arthrography.

Study design

All patients were assessed at baseline and after three months during which they were treated by a physical therapist. The treatment consisted of intensive passive end range mobilisation techniques which aimed at stretching the contracted shoulder capsule and increasing glenohumeral mobility. During one treatment session various passive arthrokinematic movements (rolling, gliding, rotating, and distractions) were performed by the therapist in various end range positions of the glenohumeral joint.[9] Patients were treated twice a week, for a maximum of three months at the department of physical therapy of the Leiden University Medical Centre. In cases where the ROM increased satisfactorily, the individual therapist could adapt the number of treatment sessions.

Clinical assessments

At baseline patient characteristics (sex, age, and disease duration) were recorded. Pain at rest, during movement, and during the night was measured with a visual analogue scale (VAS), a 100 mm horizontal line with "0 = no pain" at the left side and "100 = extreme pain" at the right side. Active and passive abduction, forward flexion, and external rotation of both shoulders were measured by conventional goniometry according to the standards of the American Academy of Orthopedic Surgeons.[10] Three months after the start of treatment patients were asked to indicate the overall result of the treatment on a five point scale (1 = poor, 5 = excellent), and assessments of pain and mobility of the shoulder were repeated. All assessments were done by one physical therapist (HMV).

Three dimensional measurements with the "Flock of Birds" electromagnetic tracking device

After the clinical assessments both shoulders were measured with the Flock of Birds electromagnetic tracking device (Ascension Technology Corp, Burlington, VT, USA). The patient was seated in a chair on a wooden platform facing a mirror in front of the transmitter. Three sensors were used to measure the rotations of the thorax, scapula, and humerus. The thorax sensor was adhered to the sternum with double sided tape and covered with Fixomull stretch self adhesive bandage (Beiersdorf AG, Hamburg). The humerus sensor was attached to a circular cuff fastened around the upper arm. The scapula sensor was mounted on a three rod device (scapula locator) with two adjustable beams to locate the positions of the angulus acromialis, trigonum spinae, and angulus inferior. Once fitted to the individual scapula, the rods were fixed into a rigid triangular construction.[4 6]

A fourth sensor was mounted on a pointer, which was used as a spatial digitiser with a tip diameter of approximately 1 mm. This digitiser was used to palpate 12 bony landmarks of the thorax and shoulder girdle in a standardised way. The bony landmarks were palpated and subsequently touched by the spatial digitiser. The position and orientation of the spatial digitiser were recorded together with the other receivers on the thorax and humerus. This palpation technique has been described by van der Helm and Pronk[11] and obtains the three dimensional positions of the bony landmarks of the shoulder with respect to the sensors. These positions can be used to define local bone coordinate systems, based on the anatomy of the individual shoulder. To construct a local coordinate system of a bony structure at least three non-collinear bony landmarks are required.

The processus xyphoideus, incisura jugularis, processus spinosis of C7 and Th8 were used to define the local coordinate system of the thorax. The angulus acromialis, trigonum spinae, and angulus inferior of the scapula were used to define the local coordinate system of the scapula.

Figure 1 Palpating angulus acromialis, trigonum spinae, and angulus inferior of the scapula with the scapula locator.

On the humerus, however, the medial and lateral epicondylus are the only suitable landmarks that can be discerned by palpation with the spatial digitiser. The essential third landmark, the glenohumeral rotation centre, is estimated from the position of five scapular bony landmarks using linear regression equations according to the method described by Meskers *et al*.[12]

By using this regression, the regressors—that is, the angulus acromialis, trigonum spinae, angulus inferior, acromioclavicular joint, and the processus coracoideus, are expressed in relation to the position of the scapular sensor in order to estimate the glenohumeral rotation centre. After relating the position of the glenohumeral rotation centre to the humerus sensor, a local coordinate system of the humerus can be defined.[12] The orientation of the local coordinate systems with respect to each other was expressed in Euler angles.[4 11 13] During motion, the position of the bony landmarks can be reconstructed from the position and orientation of the sensors on humerus, scapula, and thorax.

Recordings started with both arms hanging down by the body in the resting position. Both arms were raised simultaneously in three planes: forward flexion, scapular abduction, and abduction in the frontal plane. Three replicated movements were performed in each plane to the maximum possible active elevation of the arms. To accomplish this, patients were asked to point with the index finger to marks on two semicircular pipes mounted beside the chair. These marks were 10° apart with a total of 19 marks covering the range of elevation of the arm from 0° to 180°.

Bone positions and orientations were recorded while the scapula locator was positioned on the scapula (fig 1). With every 10° of elevation the scapula locator was readjusted to the bony landmarks of the scapula and a new recording was made, measuring the positions and orientations of all sensors simultaneously. In this way a discrete measurement at a number of arm positions was obtained. Although the measurements were static, as the arm was held still in each recorded position, these recordings can be regarded as representative of dynamic movements.[14]

A complete recording session of both shoulders, including mounting and demounting of the patient with the tracking device and performing both the initial and the position measurements, lasted about 50–60 minutes.

Statistical analysis

The results of the clinical assessments of the affected and the unaffected shoulder before and after physical therapy were tested for normal distribution using the Kolmogorov-Smirnov test.

Table 1 Results at baseline and after three months physical therapy (n=10)

	Baseline				Follow up		
	Non-affected shoulder Mean (SD)	Affected shoulder Mean (SD)	Mean difference Mean (SD)	p Value	Affected shoulder Mean (SD)	Change Mean (SD)	p Value
Pain scores on VAS (0–100 mm):							
Pain at rest	NA	28 (17)	NA	NA	22 (25)	6 (7)	0.490
Pain during movement	NA	63 (25)	NA	NA	26 (24)	37 (12)	0.013*
Pain at night	NA	44 (38)	NA	NA	12 (13)	32 (11)	0.019*
Goniometry in degrees:							
Forward flexion							
Active	156 (15)	97 (17)	−59 (28)	0.000*	127 (21)	−30 (16)	0.000*
Passive	167 (16)	104 (16)	−63 (28)	0.000*	134 (22)	−30 (18)	0.001*
Abduction (in frontal plane)							
Active	164 (16)	75 (21)	−89 (30)	0.000*	127 (33)	−52 (22)	0.000*
Passive	173 (15)	81 (23)	−92 (32)	0.000*	134 (32)	−52 (23)	0.000*
External rotation							
Active	60 (16)	22 (13)	−38 (14)	0.000*	37 (14)	−15 (16)	0.018*
Passive	69 (14)	29 (13)	−40 (13)	0.000*	47 (14)	−18 (18)	0.010*
Mean slopes with Flock of Birds:							
Forward flexion	0.458 (0.087)	0.725 (0.083)	0.267 (0.092)	0.000*	0.662 (0.139)	0.063 (0.145)	0.202
Scapular abduction	0.504 (0.100)	0.719 (0.094)	0.215 (0.161)	0.002*	0.671 (0.102)	0.048 (0.102)	0.169
Abduction in frontal plane	0.494 (0.135)	0.958 (0.356)	0.464 (0.389)	0.004*	0.694 (0.234)	0.264 (0.249)	0.008*

Pain on VAS in mm (0=no pain, 100=extreme pain). NA=not applicable.
*Significant (p<0.05).

A normal scapulohumeral rhythm depends on an unrestricted movement of the humeral head in relation to the glenoid surface during the whole ROM. Studying the relation between humeral and scapular movements is therefore an important issue in the investigation of pathological shoulder movement patterns. In all three planes (forward flexion, abduction in the scapular plane, and abduction in the frontal plane) the three sets of data obtained from the three dimensional tracking device were considered as one curve and plotted in graphs with glenohumeral joint rotation on the x axis and scapular laterorotation on the y axis. Glenohumeral joint rotation was defined as the rotation of the humerus in relation to the scapula.

As the raw data can show appreciable instrumental noise, smoothing with P splines was applied to the raw curves.[15] The common element in the curves was the upward sloping part; it was approximated by a straight line, using segmented linear regression. Within this analysis, determining the turning point of the slope was essential to compute the beginning of the slope. Only the points with scapular laterorotation higher than 5° were selected in the regression. The slope of the regression line can be seen as a summary measure for the ratio of the rotation of the scapula and the humerus.

All differences between the slopes of the movement curves and all other outcome measures between the affected and unaffected side and between the affected side before and after treatment were tested by a paired t test. The (non-parametric) Wilcoxon signed rank test was applied in those situations where an atypical point might influence the (parametric) t test unduly.

All statistical analyses were done with Matlab 5.3 (The Mathworks Inc, Natick, MA, USA) and SPSS 9.0 (SPSS Inc, Chicago, Illinois, USA).

RESULTS
Basic characteristics of the patients
Ten patients (two men, eight women) with a mean age of 49.1 years (SD 5.6) participated in the study. All had a unilateral frozen shoulder (three on the left hand side and seven on the right hand side) with a mean duration of shoulder complaints of 11.4 months (SD 8.2). Before enrolment in this study five patients had received one or more injections with corticosteroids in the shoulder by their general practitioner

(median 2, range 1–5) and 8/10 patients had undergone physical therapy treatment elsewhere (number of treatment sessions: median 37, range 6–100). Table 1 shows the basic clinical data.

Clinical assessments and three dimensional shoulder movement patterns of the affected and unaffected sides at baseline
At baseline the pain score during movement as measured with the VAS was significantly higher than pain at night and pain at rest (both p values <0.05). Mean active and passive mobility as measured with a goniometer in forward flexion, abduction, and external rotation of the frozen shoulders was significantly decreased in comparison with the non-affected shoulders at baseline. In all cases the unaffected side showed normal ROM[10] during the baseline assessments.

Figures 2A–C show a typical example of the raw and adapted output of the Flock of Birds system in one patient. The thin lines represent the raw curves and the thick lines represent the smoothed curves. Scapular laterorotation is plotted on the y axis and glenohumeral joint rotation on the x axis, for the three movement directions forward flexion (fig 2A), scapular abduction (fig 2B), and abduction in the frontal plane (fig 2C), respectively. Both the results of the affected and the non-affected shoulder are depicted in every figure.

Figures 3A–C show the mean smoothed curves of all 10 patients of both affected and non-affected shoulders at baseline. As the curves of the affected side are all above the curves of the unaffected side the former show earlier and more scapular movement in relation to glenohumeral movement than the curves of the unaffected side. The glenohumeral angle in the affected shoulders, as projected at the end of the curve on the x axis, is decreased in comparison with the unaffected shoulders.

Figures 4A–C show the slopes of the curves of the affected and unaffected shoulders at baseline. Although there is some individual variety, the slopes of the affected side are, in general, higher than the slopes of the unaffected side in all three movement directions. As can be seen in table 1, the mean slopes of the frozen shoulders are significantly higher than those of the unaffected side in all movement directions (all p values <0.005).
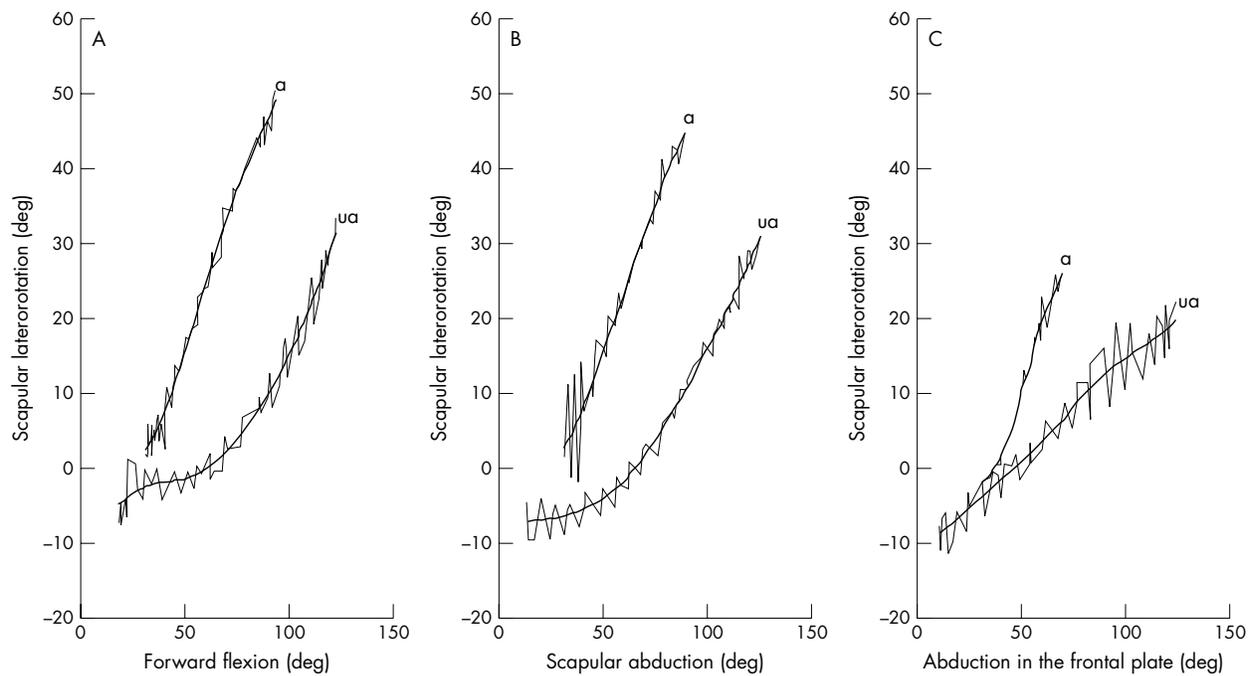
Figure 2   Raw data and smoothed curve (thick line) of one patient. a, Affected shoulder; ua, unaffected shoulder.

Clinical assessments and three dimensional shoulder movement patterns before and after physical therapy

After three months the mean number of treatment sessions was 18.7 (SD 6.5). In three patients treatment was stopped within three months (after 6, 10, and 14 treatment sessions, respectively) because of a satisfactory result. Four patients rated their overall progress as excellent, three as good, two as reasonable, and one as moderate. Table 1 gives the clinical results for pain and ROM. Mean scores for pain during movement and pain at night decreased significantly, whereas the improvement of the pain score at rest did not reach statistical significance. At follow up mean active mobility increased significantly in forward flexion (p<0.005), abduction in the frontal plane (p<0.005), and external rotation (p<0.05). Similar significant changes were seen for the passive movements.
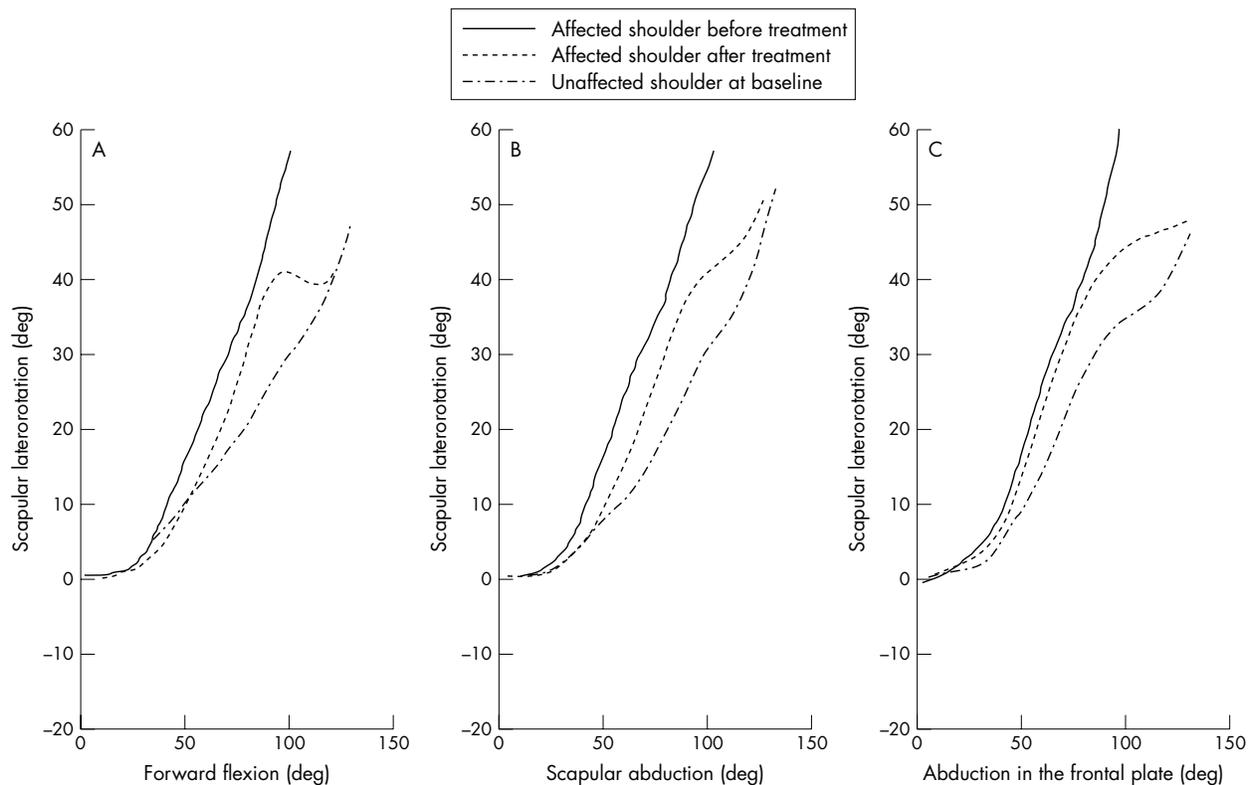

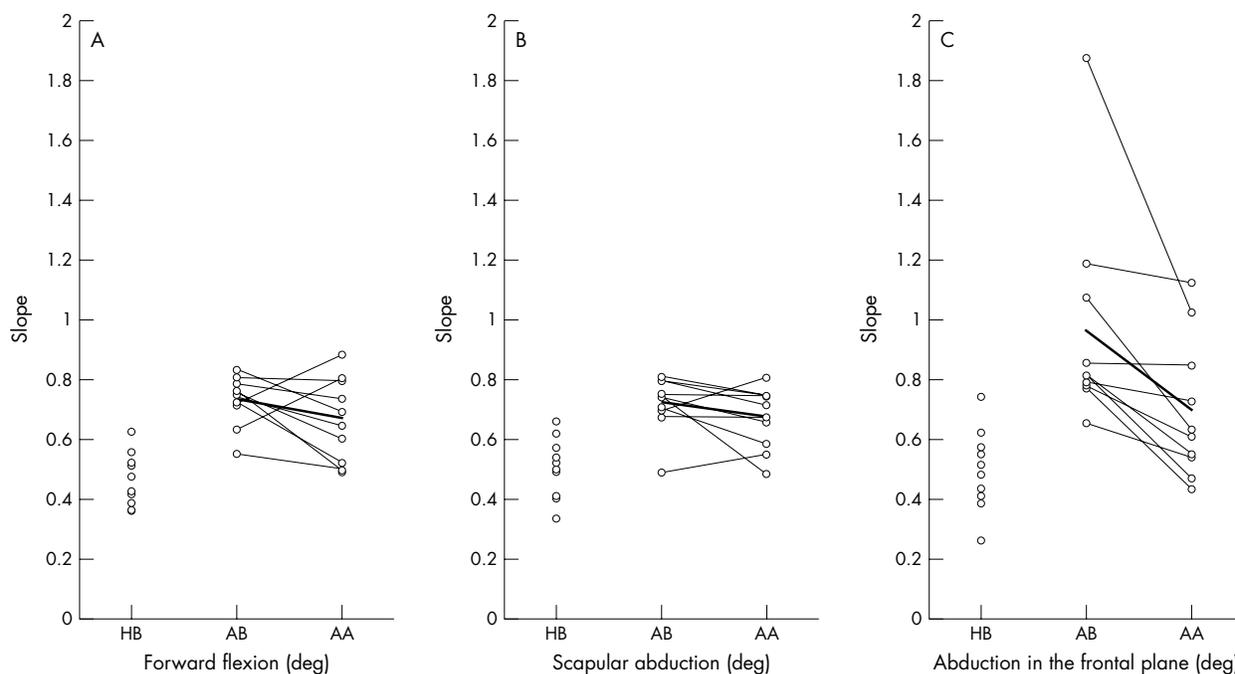**Figure 3**   Mean curves of 10 patients.

Figure 4 Slopes of 10 patients. HB, Unaffected shoulder at baseline; AB, affected shoulder before treatment; AA, affected shoulder after treatment; thick line, mean slope.

At follow up a change of the movement patterns of the frozen shoulders could be seen in all movement directions (figs 3A–C).

Figures 4A–C show the slopes of the curves before (AB) and after treatment (AA) for each patient. The thick line shows the mean change of the slopes. The largest variety and change of the slopes is seen in the abduction in the frontal plane (fig 4C). As seen in fig 4C, one patient had a steep slope before treatment and a large improvement after treatment. As such an atypical point might influence the (parametric) t test unduly, we also applied the (non-parametric) Wilcoxon signed rank test; which resulted in p=0.005, which did not change the conclusion about significance.

Although the slopes were less steep after treatment in all three movement directions, the change of the mean slopes at follow up only reached significance for the abduction in the frontal plane 0.264 (SD 0.249, p=0.008) (table 1).

Except for the slope of the curve of the three dimensional tracking system in abduction in the frontal plane, a significant difference in comparison with the unaffected side remained for all three dimensional and clinical measurements (data not shown).

DISCUSSION
In this study it was shown that by means of an electromagnetic tracking device the abnormal movement pattern of the shoulder girdle in patients with a frozen shoulder could be described and quantified. It was demonstrated that, in comparison with the unaffected shoulder, scapular laterorotation of the frozen shoulder occurred earlier and was larger during forward flexion, scapular abduction, and abduction in the frontal plane. The movement pattern of the shoulder improved significantly after a course of physical therapy but did not reach normal values.

As far as we know, our study is the first to investigate three dimensional movement patterns of the scapula in patients with frozen shoulders and thus enable movements of different parts of the shoulder girdle relative to each other to be described and quantified. Previous studies in patients with stroke and shoulder disorders examined alterations in scapula position during movement.[7 8] Our observational study included only a small number of patients. As individual variance might have affected the results, a larger group of patients is needed to confirm the characteristic three dimensional movement patterns of the frozen shoulder as described in this study. Also, healthy people and patients with other shoulder disorders should be included in further investigations to determine the specificity of this device.

The shoulder girdle is a complex joint, with its movements being characterised by their complexity in three dimensions. The normal function of the shoulder girdle is not an addition of movements in separate joints but demands a close coordination of all elements. Impairment in one part of the shoulder girdle directly affects the whole chain. Therefore a technically advanced system is needed to investigate these complex mechanisms. Registration of shoulder movement patterns can be performed in two dimensions by videotape recording or fluoroscopy. Despite the relatively fast and easy way to record these movement patterns, the value of these non-invasive procedures in measuring the kinematic pattern of the shoulder is limited owing to the inaccessibility of the scapula to external markers.[1] Three dimensional registration by optoelectronic measurement systems[16 17] has been optimised in the past decade but remains a measurement of limb motion and not rotations and translations, such as those that occur in the articulations themselves.[1]

The introduction of electromagnetic tracking systems with multiple sensors permits greater opportunities in digitising positions of several bones of the shoulder girdle simultaneously. The first studies with three dimensional electromagnetic tracking devices aimed at measuring ROM of the shoulder.[5 18] Jordan *et al* studied the reliability of the FASTRAK three dimensional tracking system with multiple sensors and found intraclass correlation coefficients for intraobserver and interobserver reliability higher than 0.60.[3] Development of the scapula locator made it possible to measure scapula positions in a fast, easy, and reliable way.[4 6 19 20] In other studies with an electromagnetic tracking device only healthy volunteers with asymptomatic shoulders were used.[3 4 6 19] In the studies of Johnson and Ludewig three or four elevation angles of the humerus and the associated positions of the scapula were

measured in healthy volunteers.[6][19] Three dimensional electromagnetic tracking systems have also been applied in measuring ROM of the cervical and lumbar spine. A good reliability for cervical range of motion was shown by Jordan et al,[3] and the study of van Herp et al disclosed a good level of agreement of the 3Space Isotrak System in measuring lumbar spine kinematics compared with three dimensional x ray measurements.[2]

Investigating three dimensional shoulder movements under pathological conditions has not been subject to extensive research. Lukasiewicz et al investigated scapular positions at three successive static positions during elevation in the scapular plane in subjects with and without an impingement syndrome of the shoulder.[21] They used a digitising probe to palpate six bony landmarks while the arm was held in the test position. Their study suggested that altered scapular kinematics may be an important aspect of the impingement syndrome. In frozen shoulders, especially, altered scapular kinematics can be clinically observed. In our study we used a semistatic method of measuring scapular positions by means of the scapula locator and this could be interpreted as a dynamic reproduction of shoulder movements during the whole ROM in three different planes of elevation.[4]

This study showed that the laterorotation of the scapula occurs earlier in patients with a frozen shoulder to compensate for the loss of mobility in the glenohumeral joint.

This loss of glenohumeral joint mobility is probably due to capsular adhesions, which cause the humeral head not to rotate sufficiently externally and glide underneath the acromion simultaneously during elevation of the humerus in several planes. The glenohumeral joint jams and the scapula is pulled outwards earlier by the humerus during elevation. The end position of the scapula of the frozen shoulders during elevation in various planes is the same as in normal shoulders. However, this end position is reached faster; the slopes of the three dimensional tracking system are steeper. After treatment a change of the movement pattern was seen in all three planes and the glenohumeral elevation angle increased. Probably as a result of the mobilisation techniques, increased rolling and gliding of the humeral head with respect to the glenoid prevents early jamming of the glenohumeral joint. The movement patterns of the affected shoulders after physical therapy tend towards those of normal shoulders. Active and passive mobility is not restored completely in the frozen shoulders after three months of treatment compared with the values of the ROM of the unaffected side. Therefore, normalisation of the movement patterns could not be seen in this period of time. Furthermore the total time for recovery has been reported to be between one and four years, taking into account that not all patients regain normal mobility.[22]

Methods producing qualitative data can be of great value in detecting changes of kinematic properties in joint diseases. Physical therapists, who have specific expertise in restoring quantity (ROM) and quality (rhythm, coordination) of joint function, can benefit by a three dimensional measurement device that can detect changes of the movement pattern. It could be useful in the evaluation of outcome of treatment.

Measuring scapular laterorotation during glenohumeral elevation is just one of the movements that can be registered with Flock of Birds. Other bone rotations that might be determined are protraction and spinal tilt for the scapula and protraction, elevation, and axial rotation for the clavicle.[4] Also the contribution of the rotation of the humerus during elevation, which is attributed as an important movement in a normal scapulohumeral rhythm, can be investigated with this equipment.

In conclusion, this is the first study in which the movement patterns of the shoulder in patients with a frozen shoulder have been assessed by a three dimensional electromagnetic tracking system. This study shows that with a three dimensional electromagnetic tracking device changes in the movement pattern in patients with a frozen shoulder, in relation to the unaffected side, and before and after a period of treatment can be detected. Further study with three dimensional electromagnetic tracking systems is warranted to investigate other aspects of the abnormal movement pattern of the frozen shoulder and to investigate three dimensional characteristics of other shoulder disorders.

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