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Research article

Three-dimensional measurements of scapular kinematics: Interrater reliability and validation of a skin marker-based model against an intracortical pin model

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ABSTRACT

A skin marker-based motion capture model providing measures of scapular rotations was recently developed. The aim of this study was to investigate the concurrent validity and the interrater reliability of the model. Shoulder range of motion (RoM) and activities of daily living (ADL) were tested in healthy volunteers with reflective markers on the scapula and thorax. To investigate the validity, the model was compared to simultaneous data collection from markers on a scapular intracortical pin. The interrater reliability was tested by comparing the skin marker-based protocol performed by two investigators. The mean root mean square error (RMSE) and the intraclass correlation coefficient (ICC(2,1)) were calculated to determine the validity and the interrater reliability, respectively. Eight subjects were included in the validity test: female/male = 2/6, mean (SD) age 35.0 (3.0) and BMI 23.4 (3.3). The mean RMSE of all scapular rotations ranged 2.3–6.7° during shoulder RoM and 2.4–7.6° during ADL. The highest errors were seen during sagittal and scapular plane flexions, hair combing and eating. The reliability test included twenty subjects: female/male = 8/12, mean (SD) age 31.4 (4.9) and BMI 22.9 (1.7). The ICC(2,1) for measuring protraction ranged 0.07–0.60 during RoM and 0.27–0.69 for ADL, for upward rotation the corresponding ICC(2,1) ranged 0.01–0.64 and 0.38–0.60, and anterior tilt 0.25–0.83 and 0.25–0.62. The validity and interrater reliability of the model are task dependent, and interpretation should be made with caution. The model provides quantitative measurements for objective assessment of scapular movements and can potentially supplement the clinical examination in certain motion tasks.

1. Introduction

Shoulder pain and disorders are the second most common musculoskeletal complaint in primary care and the societal costs hereof

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are high [1,2]. The scapula is associated with several shoulder disorders [3–5]. It articulates with the humerus, clavicle, and thoracic cage, and is involved in three of the four shoulder joints. Several ligaments and muscles attaches to the scapula and controls the joint movements, which are crucial for maintaining normal shoulder function [6,7].

Scapular dysfunction can be primary, related to direct injury, or secondary to another shoulder structure dysfunction. The condition often includes dyskinesia and may manifest as medial border prominence or dysrhythmia [3,8,9]. Clinical examinations such as the scapular dyskinesis test or symptom alteration tests can establish the diagnosis qualitatively [3,10]. But the simple diagnosis is not necessarily useful, nor does it guide in the choice of treatment. Quantitative measures are important and can contribute with much relevant information. Comparing patient data to reference values or monitoring function over time might distinguish between differential diagnoses and support assessment of severeness and of treatment progress. But achieving these measurements is complex. The scapula is embedded underneath the skin, subcutaneous tissue, and muscles, making it hard to track its true motion [11–13]. Furthermore, the scapula moves in three anatomical planes simultaneously and moves synchronously with other shoulder joints and may also translate in the sagittal and frontal plane with respect to the thorax [6].

With a state-of-the-art optical motion capture (OMC) system, we wanted to update a previous skin marker-based model for diagnosing and monitoring scapular dyskinesia [14]. The primary aim of this study was to investigate the validity and the interrater reliability of the model for analysis of scapular kinematics during movements representing range of motion (RoM) and activities of daily living (ADL). Based on the results, our objective was also to assess the clinical application of the model.

We hypothesized that the model would be considered clinically applicable, with small measurement errors during the tested movements and with a good or excellent reliability (ICC(2,1) above 0.75, based on the guidelines by Koo et al.) [15,16].

2. Methods

2.1. Study type and trial period

This study is part of a larger controlled laboratory study investigating shoulder biomechanics. The sub-study was designed to evaluate the concurrent validity and interrater reliability of a scapula OMC model. The Danish Capital Region Ethics Committee (journal number: H-20061143) and the Capital Region Knowledge Center for Data Reviews (journal number: P-2021-334) approved the study.

The validation experiment included a single test per participant (on their non-dominant shoulder) comparing the skin marker model with kinematic analysis gold standard; a marker cluster fitted to an intracortical pin in the spina scapulae. In the reliability experiment, participants from a separate population underwent the same skin marker-based protocol (on their dominant shoulder) twice the same day with different investigators blinded to each other's performances. All trials were carried out at the Human Movement Analysis Laboratory, Department of Orthopedic Surgery, Copenhagen University Hospital Hvidovre, Denmark, in June 2021.

2.2. Subjects

Inclusion criteria for both experiments were age 18–50, BMI 18.5–30, normal shoulder function (as assessed from a standardized clinical shoulder examination), and ability to speak and understand Danish. Participants with previous shoulder pathology (including

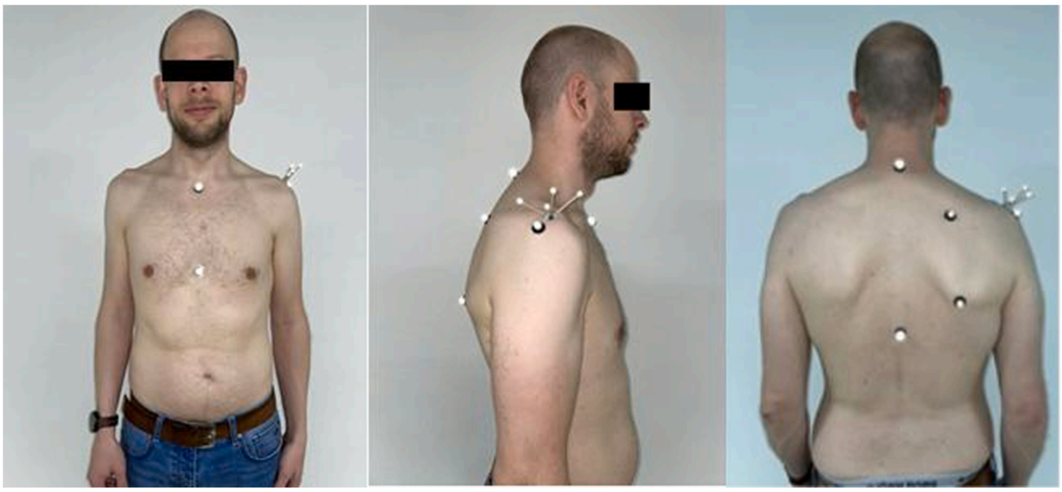

Fig. 1. The skin marked-based motion capture model marker configuration. The scapula was fitted with the acromion marker cluster and markers on the scapular acromion angle, inferior angle and trigonum scapula (6.4 mm diameter markers). There were four thoracical markers on the 7th cervical and 8th thoracic vertebrae, the jugular notch and on the xiphoid process (14 mm diameter markers).

fractures; joint dislocations; tendon or muscular disorders; or other atraumatic pathologies) were excluded. Participants were allowed to participate in one of the two experiments. All participants signed a written informed consent form.

2.3. Kinematic model

The skin marker-based model is an adaption of the model developed by Jackson et al. [14]. In the current model the clavicle is removed and the scapula is given six degrees-of-freedom (DoF). In the skin marker model, reflective spherical markers were attached to predefined anatomical positions on the scapula (6.4 mm diameter markers) and thorax (14 mm diameter markers), in accordance with International Society of Biomechanics (ISB) recommendations (Fig. 1) [17]. The marker trajectories were collected at 100 Hz using twelve infrared light-emitting cameras (T40, Vicon motion systems Ltd., Oxford, GB). Data were reconstructed using inherent computer software (Nexus 2.10, Vicon motion systems Ltd.), and further processed and analyzed using custom made MATLAB scripts (MathWorks Inc., Natick, MA, USA). A static calibration, consisting of 500 frames, was performed to enable optimal marker identification and definition of the individual segments of each participant standing with both shoulders in neutral position, elbows flexed to 90° and neutral wrist. In the skin marker model, the center of rotation and joint coordinate system of the scapula were defined according to the models by Michaud et al. and Jackson et al. and did not include a functional calibration, as previous research found that functional methods tend to be more variable than anatomical, without increasing validity [14,18]. For the intracortical pin model, an additional functional calibration was performed with the subject performing two repetitions of shoulder flexion-extension, abduction-adduction, axial rotations, and circumduction [18,19].

The selected motion tasks were dynamic movements and reflected both shoulder RoM, which are usually performed during the clinical examination, and ADL, which often provoke symptoms in patients with shoulder pathology. The motion tasks are listed in Table 1. All movements started with the participant standing with the arm in neutral rotation along the body and were completed when the motion task had been performed and the arm was brought back to the starting position. For RoM tasks, the participants were instructed to reach their individual maximal capacity, while the ADL tasks had specific end points (e.g., the mouth in eating task). All movements were consecutively repeated seven times. The participants were guided by a metronome rhythm and an investigator performing all movements synchronized.

2.4. Instrumentation for validation experiment

The participants received oral pain relief (1 g paracetamol) 1 h prior to the procedure. The instrumentation with the bone-pin was performed by an orthopedic senior consultant under sterile conditions with the subject lying on their dominant side. Local anesthesia (Ropivacain 5 mg/ml) was injected from the skin and subcutaneous tissue to, and including, the periosteum at the insertion site on the non-dominant limb. A skin stab incision of approximately 5 mm was made. One stainless steel self-drilling pin (2 mm in diameter) was oscillated 15–20 mm into the lateral part of the scapular spine (Fig. 2). The pin was placed to avoid interference with muscles, nerves and blood vessels and shortened to approximately 2.5 cm over the skin. A cluster of four markers (6.4 mm in diameter) was rigidly placed on the pin and the insertion sites cleaned and covered. The positions of the markers on the skin and the pin were controlled prior to data collection.

The markers and pin were removed after data collection, and the incisions closed with adhesive strips and band-aid. Pain relief (oral paracetamol) and prophylactic oral antibiotics (flucloxacillin, 1 g three times daily) were given for four days following the experiment. A follow-up on function and pain was made by telephone after two and five days.

2.5. Reliability experiment

In the reliability experiment, the skin marker-based protocol was used to test the dominant shoulders of the participants twice on the same day, with separate investigators.

Following the first series of measurements, the responsible investigator removed all markers, and traces on the skin were removed with alcohol. Another investigator, blinded to the initial marker placement, put the markers on the subject for the second series. The

Table 1
Experimental motion tasks representing range of motion and activities of daily living. All motion tasks were performed dynamically from the starting position reaching maximal range of motion and back without a pause and were all repeated consecutively seven times.

Movements		
Range of motion (RoM)		Rhythm (beats per minute)
Flexion	Full RoM elevation in anterior sagittal plane, neutral rotation	55, 4 beats per task repetition
Scaption	Full RoM abduction in scapular plane, neutral rotation	60, 4 beats per task repetition
Extension	Full RoM elevation in posterior sagittal plane, neutral rotation	50, 2 beats per task repetition
Abduction and external rotation (ABER)	0–90° abduction, neutral-to-external axial rotation	55, 4 beats per task repetition
Abduction and internal rotation (ABIR)	0–90° abduction, neutral-to-internal axial rotation	55, 4 beats per task repetition
Activities of daily living (ADL)		
Reaching back pocket	Neutral-to-extension, neutral-to-internal axial rotation	60, 4 beats per task repetition
Eating	Neutral-to-flexion, adduction	55, 2 beats per task repetition
Hair combing	Neutral-to-flexion, neutral-to-external axial rotation	60, 4 beats per task repetition

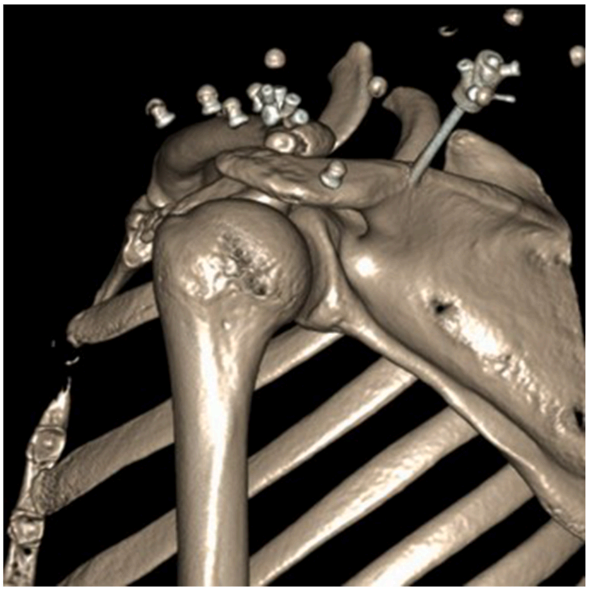

Fig. 2. Computed tomography scan of scapula with pin and markers.

participants were instructed not to convey any information on the previous placement of the markers. A second series of measurements was then acquired. After the second series, the markers were removed. No medications were prescribed to these participants. A follow-up was made by telephone after two days.

2.6. Outcomes

The primary outcome was the measurement error of the skin marker-based model, defined as the mean root mean square error (RMSE), as compared to the synchronous measurements from the markers on the intracortical pin (pairwise comparison). The interrater reliability, assessed from the intraclass correlation coefficient (ICC(2,1)), was the secondary outcome. Other outcome measures were the shoulder RoM and the Western Ontario Shoulder Instability Index (WOSI) score. The WOSI score is a validated self-assessment of shoulder function with 21 items ranging from 0 to 100 on a visual analogue scale (VAS) and a total score of 2100 (0 no deficit and 2100 the worst) [20].

2.7. Data processing, reduction, and statistical analysis

A personalized 2-joints and 12 DoF kinematic model of the upper limb, consisting of the thoracohumeral (six DoF) and the acromioclavicular (six DoF, representing the scapula), was constructed for each participant. The joint centers were located using anatomical or predictive methods as recommended by Michaud et al. [18]. The static posture was used as reference pose with all angles defined as zero. The joint kinematics were reconstructed using an extended Kalman filter implemented in the Biorbd biomechanical toolbox based on the technical markers for the skin marker model, and on the markers on the pin for the pin model [21,22]. For all the trials, the acromioclavicular joint angles time histories were extracted from the model output.

The time-dependent joint angle data from each motion task were cut to separate each repetition. This process was automated and manually corrected if needed for the validity test, as opposed to the reliability test where the cutting was solely done manually. The first and last repetition were excluded due to possible discrepancies associated with initializing and terminating the motion task. Each repetition was time normalized to the same number of data ($N = 1000$) points using a spline interpolation. For the validity test, the RMSE between the joint angles obtained from the skin markers and the pin markers was computed for each repetition and subject followed by a mean RMSE computation of all eight subjects for each motion task and DoF. In the reliability test, the initial joint angle was set to zero to standardize the measurements. The ascending part of the motion task, i.e., the first 50 % of the data points of each repetition, was used for analysis. Subsequently, the root mean square (RMS) was calculated from the joint angle data obtained from the two measurements series. A mean RMS of the remaining five repetitions was computed. Finally, the ICC(2,1) calculation was carried out based on all 20*2 (subjects*investigators) mean RMS values for each motion task and DoF.

Ethical considerations, in line with previous studies, led to recruitment of eight volunteers to participate in the invasive validation experiment [23–25]. The guidelines published by Koo et al., in 2016 were used to indicate the level of reliability [16]. Values of less than 0.5 were considered as poor, 0.5–0.75 as moderate, 0.75–0.9 as good, and greater than 0.90 as excellent. For the reliability analysis, a sample size of twenty was chosen based on our hypothesis that the ICC(2,1) would be above 0.75, with two investigators per subject, a power of 90 % and alpha set to 0.05 [26].

3. Results

Demographic data and shoulder RoM measures are shown in Table 2. All participants were able to complete the study protocol. No adverse events were seen during or after the experiments.

3.1. Validity

All mean RMSEs were below 8° (Table 3). The mean RMSEs ranged 2.3–6.7° during shoulder RoM tasks and 2.4–7.6° during ADL. The lowest registered mean RMSE overall was 2.3° in anterior-posterior tilt during the extension task. For upward-downward rotation, the lowest mean RMSE was also found during extension. The lowest RMSE for protraction-retraction was 3.8°, during abduction and internal rotation (ABIR). Overall, the highest RMSEs were found during motion tasks where the arm was elevated in front of the body and/or above 90° (flexion, scaption, eating and hair combing) while the lowest were found during movements that included sagittal plane extension (full RoM extension and reaching back pocket). The captured protraction-retraction was larger in the skin marker model than in the pin model in all eight motion tasks (Table 4). This was also the case for upward-downward rotation, except for the abduction and external rotation (ABER) task, where the pin markers captured 0.2° larger range of rotation. On the contrary, the anterior-posterior tilt was smaller in the skin marker model in five motion tasks.

3.2. Reliability

The ICC(2,1) values of the eight motion tasks ranged from 0.01 to 0.83 (Table 5). There was not a certain motion task that showed consistent ICC values. During the RoM tasks, the ICC from flexion and ABER were above 0.5 in two out of three scapular rotations. The ICC during hair combing were above 0.5 for upward-downward rotation and anterior-posterior tilt, but below 0.75. For the remaining motion tasks, ICC were above 0.5 for maximally one rotation. The ICC of upward-downward rotation was above 0.5 in five of the eight motion tasks, but all were below 0.75. The lowest ICC overall was also found for upward-downward rotation, during the extension task. The highest ICC overall was for anterior-posterior tilt during ABER.

4. Discussion

The mean RMSE of the skin marker-based OMC model was less than 8° in all tested motion tasks, as compared to an intracortical pin model, which supports our first hypothesis, indicating acceptable validity of the model for clinical use [15,27,28]. Setting a limit of acceptable validity is arbitrary, and clinicians must cautiously assess which motion tasks they find useful. In this experiment, the RMSE for measuring protraction-retraction were more than half the range of motion during all three ADL tasks, and the authors would therefore not recommend using these tasks in treatment decision making, while the errors for upward-downward rotations and anterior-posterior tilt were much smaller from a percentual perspective and may be considered for clinical use (Tables 3 and 4).

The ICC(2,1) ranged from 0.01 to 0.83. The ICC values were non-consistent, as they were task dependent and not necessarily similar for the three scapular rotations. These results were lower than hypothesized.

Skin marker-based OMC technique has been used for clinical gait and running analyses in the last decades and we wanted to assess the clinical application of the technique for analysis of scapular kinematics [14,29–33]. Even though the validity seems promising for clinical use, the interrater reliability was not good enough overall. The model might supplement other examinations in certain motion tasks and specific scapular planes, with cautious interpretation. For RoM tasks, ABIR and ABER could be considered for upward-downward rotation and ABER and extension for anterior-posterior tilt. The ADL tasks with clinical potential include hair

Table 2
Demographic data. BMI: Body mass index. WOSI: Western Ontario Shoulder Instability index (range 0–2100).

	Validation experiment	Reliability experiment
Participants, n	8	20
Female/male sex ratio, n (%)	2 (25)/6 (75)	8 (40)/12 (60)
Age, mean (range), years	35 (29–38)	31 (23–37)
Height, mean (SD), cm	178 (12.6)	177 (7.1)
Weight, mean (SD), kg	75.0 (18.0)	71.6 (8.2)
BMI, mean (SD)	23.4 (3.3)	22.9 (1.7)
Dominant side, n (%), right/left	7 (87.5)/1 (12.5)	16 (80)/4 (20)
Upper limb physical activity		
0 times/wk., n (%)	0 (0)	1 (5)
1-3 times/wk., n (%)	3 (37.5)	13 (65)
>3 times/wk., n (%)	5 (62.5)	6 (30)
Total physical activity, mean (SD), hrs./wk.	8.5 (6.2)	7.2 (4.4)
Total WOSI score, mean (SD)	25.8 (31.8)	58.8 (74.3)
Range of motion, mean (SD), degrees	Non-dominant shoulder	Dominant shoulder
Flexion	173 (3.5)	171 (2.9)
Abduction	165 (7.1)	171 (2.9)
External rotation	74 (11.1)	73 (4.3)
Internal rotation	70 (11.5)	65 (1.9)

Table 3
Mean root mean square errors (RMSE) of the skin marker-based model compared to an intracortical pin model. Values represent degrees. ABER: abduction and external rotation. ABIR: abduction and internal rotation.

Motion task	Flexion	Scaption	Extension	ABER	ABIR	Reaching back pocket	Eating	Hair combing
Protraction-retraction	6.7	6.4	4.0	4.5	3.8	4.0	6.6	7.6
Upward-downward rotation	5.2	5.8	2.6	4.0	3.8	2.7	5.8	5.1
Anterior-posterior tilt	3.3	3.9	2.3	2.4	2.7	2.4	4.0	3.0

Table 4
Mean range of scapular rotations during range of motion tasks and activities of daily living captured from pin markers and skin markers, respectively (degrees). ABER: abduction and external rotation task. ABIR: abduction and internal rotation task.

	Flexion	Scaption	Extension	ABER	ABIR	Reaching back pocket	Eating	Hair combing
Pin markers, mean (SD)								
Protraction-retraction	14.9 (4.2)	14.3 (6.2)	14.6 (3.5)	11.0 (4.7)	9.0 (2.6)	7.3 (2.6)	11.1 (5.4)	16.1 (5.7)
Upward-downward rotation	42.8 (4.2)	46.6 (5.0)	8.5 (3.5)	31.3 (5.3)	22.5 (6.0)	8.4 (2.7)	29.4 (6.7)	45.8 (4.2)
Anterior-posterior tilt	30.6 (8.6)	31.0 (6.1)	10.4 (5.7)	21.8 (5.5)	12.7 (3.3)	9.5 (3.0)	19.8 (5.2)	32.1 (7.6)
Skin markers, mean (SD)								
Protraction-retraction	17.4 (6.0)	16.9 (7.3)	20.0 (4.6)	18.1 (7.1)	11.1 (3.3)	8.9 (3.6)	18.1 (8.1)	16.7 (7.5)
Upward-downward rotation	47.1 (4.6)	49.5 (5.9)	10.0 (3.8)	31.1 (6.9)	23.5 (5.7)	11.1 (3.2)	37.3 (6.8)	50.7 (7.4)
Anterior-posterior tilt	28.3 (11.7)	33.0 (7.7)	9.6 (5.0)	23.2 (6.0)	12.3 (3.8)	8.4 (2.8)	15.6 (7.3)	33.8 (9.6)

Table 5
Intraclass correlation coefficient ICC(2,1) values from the reliability experiment. ABER: abduction and external rotation task. ABIR: abduction and internal rotation task.

Motion task	Flexion	Scaption	Extension	ABER	ABIR	Reaching back pocket	Eating	Hair combing
Protraction-retraction	0.60	0.07	0.42	0.44	0.31	0.27	0.69	0.44
Upward-downward rotation	0.57	0.29	0.01	0.64	0.60	0.51	0.38	0.60
Anterior-posterior tilt	0.25	0.38	0.54	0.83	0.30	0.33	0.25	0.62

combing and reaching back pocket for upward-downward rotation and hair combing for anterior-posterior tilt.

Skin marker-based OMC methods allow three-dimensional kinematic analysis while having the advantage of being non-invasive and non-irradiating, but is not flawless [11,15,29,34]. A known limitation is the inherent skin motion artifacts due to the overlying skin being loosely connected to the bone, meaning that the skin markers do not track the true motion of the scapula [11–13]. To overcome this, the method has been continuously refined, including the introduction of the acromion marker cluster (AMC) and improvements in data reconstruction [14,15,30–33]. But despite technical and mathematical ways to minimize skin motion artifacts, it cannot be eliminated. Furthermore, individual differences in subcutaneous fat may influence the precision and lowering the validity. In the present study all subjects were lean with normal BMI.

This is, to our knowledge, the first study to investigate the validity of an OMC model using an AMC on subjects performing both RoM and ADL. Even though clinical examinations often focus on single plane RoM, ADL might represent movements and positions where symptoms are provoked better. These often include raising the arm above the shoulder height and our results show, in line with previous results, higher measurement errors in movements where the arm is elevated above 90° [11]. Still, the validity during both RoM and ADL tasks is promising.

A previous validation of an OMC model against dynamic x-ray found mean RMSEs below 10° during RoM tasks, similar to the present study, except for upward-downward rotation during internal-external rotation of the arm [35]. They found a high correlation between the OMC and x-ray techniques and concluded that skin marker-based OMC is useful for analyzing scapular kinematics. Other OMC models using the AMC and single calibration also found mean RMSEs below 10° during elevation in various planes [30,36–39]. None of these validated the skin marker model against markers on intracortical pins, however. More recently, a setup similar to the present study compared an AMC model to a scapula locator at end range elevation, depression, protraction and retraction of the clavicle without elevating the arm, reporting mean RMSEs for the scapular rotations of less than 10° [40].

Both biological and methodological discrepancies may have influenced the inconsistent ICC values and thus the reliability in the present study. The movements involved may, to a different extent, be prone to variation in execution, both in temporal-spatial timing and in RoM. Methodological factors affecting the reliability primarily consist of marker placement accuracy and consistency related to training and experience of the investigator [41,42]. The results might thus have turned out differently with other participants and/or investigators [43].

The interrater reliability of the model is considered poor to moderate [16]. Several previous studies of scapular kinematics have showed that reliability is negatively affected by arm elevation above shoulder height [11,30,44]. The present study did not examine the influence of elevation, but the complete movement. This could mean that the reliability from the five tested motion tasks with elevation to or above shoulder height in this study, might fluctuate significantly during the motion. However, as the inconsistency were also seen during motions with less shoulder elevation, it is not possible to conclude the extent of influence hereof. Another test-retest setup have reported interrater reliability ICC values with a similarly wide range from 0.29 to 0.84 [30]. Their highest values were obtained from measuring protraction-retraction and upward-downward rotation, while anterior-posterior tilt showed generally lower ICC. The highest ICC obtained in this study were of upward-downward rotation, while the ICC of protraction-retraction were generally the lowest. Bourne et al., using electromagnetic tracking like the aforementioned, concluded that the reliability of their skin marker-based model was both task dependent and non-uniform for the three rotations [29]. Further, with the lowest ICC values found for protraction-retraction, their results seem similar to the present study. Nevertheless, it is important to note that they had a different technical setup and the intrarater reliability was investigated. Additional studies have investigated the reliability of different scapular kinematic models and reported promising results, but varying experimental setup and statistical methods complicates direct comparison of the results [37,42].

This study has several limitations. Especially for the validation experiment, the study population was small, yet similar to previous reports. The number of participants in the reliability experiment was also limited but based on a statistical sample size calculation. We chose to include both male and female subjects, as previous studies did not report kinematical differences related to sex [11,39]. Even though the populations were considered homogenous and fulfilled the aim of representing typical young traumatic shoulder patients, the measured scapular rotations during RoM and ADL varied between subjects (as suggested by the size of the standard deviations). The validation experiment motions were captured while the subjects had intracortical pins in both the humerus (for another experiment) and the scapula and, further, in their non-dominant arm, which might influence the shoulder kinematics [45]. As previously mentioned, a different experimental setup as well as statistical methods could influence the results. However, the technical accuracy could hardly have been optimized by a different setup, which was based on recommendations from the manufacturer and on the feasibility at our clinical facility [46].

Our results indicate that this easily performed protocol might be useful for testing certain shoulder RoM and ADL motion tasks in the clinical setting, as a supplement to other examinations. The interrater reliability varied from poor to moderate, meaning that the results from different investigators should be interpreted cautiously. The clinical potential might be further determined by investigating the intrarater and intrasubject reliability. Also, the model needs to be tested in patients to prove its feasibility in the clinical setting.

5. Conclusion

This study investigated the concurrent validity and interrater reliability of a non-invasive OMC model for three-dimensional assessment of scapular kinematics. Compared to an intracortical pin model, the measurement errors were $<8^\circ$ in all scapular planes. The interrater reliability was poor to moderate depending on the motion task. Assessment of scapular kinematics using this OMC model should be made with caution and motion tasks carefully selected.

Data availability statement

Due to the sensitive nature of the questions and examinations in this study, raw data is not made publicly available. However, data and mathematical scripts may be shared upon request to the corresponding author.

CRediT authorship contribution statement

Catarina Malmberg: Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Visualization, Writing – original draft. **Stefan E. Jensen:** Writing – review & editing, Validation, Software, Methodology, Data curation, Formal analysis. **Benjamin Michaud:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – review & editing. **Kristine R. Andreasen:** Writing – review & editing, Investigation, Resources. **Per Hölmich:** Writing – review & editing, Supervision, Resources, Conceptualization. **Kristoffer W. Barfod:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Jesper Bencke:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Catarina Malmberg reports financial support was provided by the Familien Hede Nielsens Fond.

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