Precision and Accuracy Measurement of Radiostereometric Analysis Applied to Movement of the Sacroiliac Joint

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Abstract

Background Different techniques have been used to quantify the movement of sacroiliac (SI) joints. These include radiostereometric analysis (RSA), but the accuracy and precision of this method have not been properly evaluated and it is unclear how many markers are required and where they should be placed to achieve proper accuracy and precision.

Purpose The purpose of this study was to test accuracy and precision of RSA, applied to the SI joint, in a phantom model and in patients.

Methods We used a plastic phantom attached to a micrometer to obtain a true value of the movement of the

SI joint and compared this value with the measured value obtained by RSA; the difference represented the accuracy. The precision of the system was measured by double examination in the phantom and in six patients, and was expressed by a limit of significance (LOS). We analyzed different marker distributions to find optimal marker placement and number of markers needed.

Results The accuracy was high and we identified no systematic errors. The precision of the phantom was high with a LOS less than 0.25° and 0.16 mm for all directions, and in patients, the precision was less than 0.71° for rotations and 0.47 mm translations. No markers were needed in the pubic symphysis to obtain good precision.

Conclusions The accuracy and precision are high when RSA is used to measure movement in the SI joint and support the use of RSA in research of SI joint motion.

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Introduction

Because of high accuracy and precision, radiostereometric analysis (RSA), has become a well-established method for three-dimensional (3-D) measurements of micromotion in joints [9, 21]. Different radiographic modalities have been used to measure movement in the sacroiliac (SI) joint objectively [7, 12, 15], whereas five studies have used RSA to evaluate movement between the sacrum and the ilium [16–20]. With RSA, a maximum rotation of 3.6° has been measured and the translation never exceeded 2 mm in the SI joint, which is less movement than other methods have revealed [5], and for this reason the method has been questioned [3]. Despite the use of pelvic RSA in clinical research, the accuracy and precision have not been fully evaluated.

Accuracy of the measurement is the closeness of the measurement to its true value. In phantom models accuracy

reflects the level of agreement between a true value of movement and the results obtained using RSA. Systematic error (bias) of the system occurs when the differences between systems and experiments are uniform and if they can be corrected [13]. The precision (spread) of the measurement is the degree of closeness in repeated measurements under unchanged conditions. Under optimal conditions, the difference between two examinations should be zero [13].

Earlier studies have measured movement between the sacrum and the ilium with dorsally placed markers [16–20]. In these studies, the markers were placed close to the joint line, and because of the flat anatomy of the bones, the markers become collinear (in the same plane). As this is not necessarily the optimal 3-D distribution, the use of this technique has been questioned [3]. Guidelines for standardization of RSA of implants recommend at least three noncollinear markers in each segment (rigid body) [21]. A good 3-D configuration relies on the distance between the markers and the distribution of markers in all three axes, and a condition number (CN) expresses the quality of a marker segment [11]. The CN is a mathematical expression of how the markers relate to a straight line going through the segment [14]. A low CN represents a good scatter of markers in the segment. A CN less than 110 is considered a reliable distribution [21], and an upper limit of 150 is suggested. The CN will influence the precision and accuracy, and a factor of importance is how good the RSA system calculates the placement of each marker. The precision of each marker can be influenced by soft tissue disturbances and stability of the markers. If the markers are not thoroughly inserted in the bone, but end up in the soft tissue, the markers become unstable. This may occur in the sacrum because of the thick and strong dorsal ligaments covering the bone, especially in the cranial part. Unstable markers should be excluded if they move more than 0.35 mm between two examinations (mean error [ME] of rigid body fitting) [21]. Although RSA has been validated with the use of a phantom in a fracture model of the distal radius and hip and knee prostheses [8, 10, 11], it has not been validated for use in the pelvis.

We therefore (1) measured the accuracy, precision, and CNs of pelvic RSA with different marker distributions in a phantom model, (2) explored whether frontal markers around the symphysis improve the CN and precision and whether it is possible to avoid markers in the cranial part of the sacrum, and (3) compared the precision obtained by a phantom with the precision obtained by double examinations in patients.

Patients and Methods

We used a phantom model to measure accuracy and precision while precision was measured in six patients. The

phantom was a full male plastic pelvis (Sawbones® 1301; Pacific Research Laboratories, Inc, Vashon, WA, USA) with detached ilium and sacrum. The left ilium was rigidly fixed to a platform and the sacrum was attached to a combined X, Y, Z translation (25 mm-PT3/M X, Y, Z Travel Translation Stage; Thorlabs, Inc, Newton, NJ, USA) and rotation stage (PR01A/M Precision Rotation Platform, Thorlabs) (Fig. 1). According to the manufacturer, the translation stage has a resolution of 0.01 mm and the rotation stage has a resolution of $1/25^\circ$ (2.4 arcmin). The movement was performed around an X, Y, Z coordinate system with the X and Y axes in the plane of the table imitating a supine position (Fig. 1). The rotations were performed in three different setups (Fig. 1). One-mm markers were used. Five markers were inserted into the ilium posteriorly and three markers into the inferior pubic ramus. Another eight markers were inserted into the dorsal aspect of the sacrum (Fig. 2). The markers defined two rigid body segments, where the ilium was defined as the fixed segment and movement of the sacrum relative to the ilium was measured. We conducted 10 double examinations to analyze the precision. Between these examinations, the equipment was fully dismantled and reset.

To evaluate different marker distributions, the eight markers in each segment were divided into four different marker segments (MS): MS A with five dorsal markers in the ilium; MS B with three frontal markers in the inferior pubic ramus; MS C with six sacral markers; and MS D with two cranial markers in the sacrum (Fig. 2). To examine the need for frontal markers, we tested MS AB against MS A. In this setting, all eight sacral markers were included. To examine the need for cranial markers in the sacrum, we tested MS CD against MS C. All eight markers in the sacrum were included. Finally, three dorsal markers in the ilium and three markers in the sacrum were randomly selected (Fig. 2, circles) and tested against eight markers.

To determine the in vivo precision, six patients received 17 double examinations. The six patients were women, selected from a group of nine patients with long-lasting pelvic girdle pain after pregnancy included in an ongoing study where SI fusion of the affected SI joint was performed. These six patients had a mean age of 38 years (range; 33–47 years), BMI of 24 (range; 21–30), and pelvic girdle pain for 10 years (range; 5–25 years). The patients were analyzed with RSA at baseline, 3 months, and at 12 months after surgery. The maximum level of CN was set to 150 and the mean error (ME) was set to 0.35. With these limitations we had six patients with one, two, two, three, three, and six double examinations respectively. When the markers in the symphysis were removed from the analysis, 11 examinations had sufficient CN and ME to perform a comparison of precision. The patients were repositioned between the examinations, without moving

Fig. 1A–C The setup of the pelvic phantom with the sacrum attached to a translation stage and a rotation rod are shown for (A) Y rotation and all translations, (B) X rotations, and (C) Z rotations.

Fig. 2 The RSA markers were divided into different marker segments (MS): MS A = five dorsal markers in the ilium; MS B = three frontal markers in the inferior pubic ramus; MS C = six sacral markers; and MS D = two cranial markers in the sacrum. Circles = three randomly selected markers in the ilium and three randomly selected markers in the sacrum.

the cameras and the calibration cage. As there is movement in two joints in each examination (one in each SI joint), movement in the right SI joint was converted to represent the left SI joint. The total movement in one double examination was the mean of these two measurements.

To conduct the displacements, three different setups were required to cover all the translations and rotations. We performed all translations and Y rotations in one setup (Fig. 1A). We performed X rotations (Fig. 1B) and Z rotations (Fig. 1C) in separate setups. To measure accuracy, the sacrum was translated and rotated using the micrometers to measure the true value of movement. The sacrum was moved from Point 0 and the translations were performed in all three directions in one move. Film pairs were taken at 0.01, 0.02, 0.04, 0.08, 0.5, 1, 2, 3, and 5 mm translation. The phantom was set to zero before rotation. Every position was examined by double examinations. To simulate a change in position, a 1-cm support was placed under the phantom between the double examinations. The rotation was measured at 0.2, 0.5, 1, 3, and 5°. A total of 66 film pairs was taken.

Each pair of radiographs was taken with two x-ray tubes (GE Proteus XR/A™ system [GE Healthcare, Piscataway, NJ, USA] and Philips OPTIMUS [Philips Healthcare, Best, The Netherlands]) at an approximately 40°-angle to each other. An UmRSA Calibration Cage Number 43 (UmRSA Biomedical, Umeå, Sweden) was used and there was a film-focus distance of 155 cm. An exposure of 133 kV and 6.5 to 8 mAs was used. The digital images were analyzed using UmRSA Version 6.0 software (UmRSA Biomedical), and the markers were identified with user-assisted edge detection (UmRSA digital measure) [22]. The maximum limit for the CN was set to 150 and the maximum level of ME was set to 0.35.

We calculated the accuracy of the RSA system using the mean difference between the measured value and the true value (d_{m-t}), and the margin of error was expressed by a 95% CI with $n - 1$ degrees of freedom [13]. The precision for translation and rotation was expressed by the mean of the absolute value of the difference between two double examinations $+ t_{(n-1)0.005} \times SD_{\text{Absolute value}}$ where t follows the Student's t -distribution with $n - 1$ degrees of freedom and 99% level of confidence. Some authors have used the expression limit of significance (LOS) [1, 4, 6] as an alternate way to express this precision. When a movement beyond this limit is found, an actual movement between the segments has occurred and the detected movement is larger than what can be explained by the measurement error. We used a paired t -test to detect any differences in accuracy and precision between different marker setups. We used SPSS® Version 18 (SPSS Inc, Chicago, IL, USA) for statistical analysis.

Results

The CN in the phantom varied from 17 to 59 in the sacrum and 29 to 117 in the ilium (Table 1). With eight markers in the ilium and eight in the sacrum the accuracy of the phantom for rotation was between -0.025° to 0.051° . The largest error was observed in the Y rotation where the

Table 1. Condition numbers in segments with different marker distributions

Location	Number of markers	Marker segment	Condition number
Ilium	8 (5 dorsal, 3 frontal)	AB	29
	5 dorsal	A	92
	3 dorsal	Circled	117
Sacrum	8	CD	17
	6	D	43
	3	Circled	59

system underestimated the result by 0.051° . The translation accuracy was better in the in-plane directions (X, Y) than in the out-of-plane direction (Z). In the Z direction, the system underestimated the value by 0.065 mm (Table 2). The precision (LOS) in the phantom was between 0.06° and 0.25° for rotation and between 0.03 and 0.16 mm for translation (Table 3).

When the markers placed in the symphysis were removed, the CN went from 29 to 92. The ME was reduced ($p < 0.001$) when the frontal markers were removed (Table 3). There was no difference in the accuracy, but the precision was reduced in the Z rotation ($p = 0.010$) and the X translation ($p = 0.003$). However, when the two cranial-placed markers were removed (MS ABCD versus MS ABC), there was a reduction ($p = 0.012$) in the accuracy of the Y translation, and the precision was poorer in the Z rotation ($p = 0.023$) and the X translation ($p = 0.005$). When three randomly selected markers were analyzed compared with eight markers, there were reductions in precision of the Y and Z translations ($p = 0.016$ and $p = 0.013$, respectively), but there was no reduction in accuracy (Fig. 3).

The precision of the measurement in the phantom was better than in the patients (Table 3). Similar CN was achieved, but the mean ME was greater in the patients than in the phantom. When the frontal markers were removed, six double examinations could not be analyzed owing to insufficient CN, and therefore they were excluded. The 11 examinations remaining for analysis showed no change in the precision (Table 3). The CN in the ilium had a mean 38 to 96 increase ($p < 0.001$) and the ME had a tendency ($p = 0.048$) to be lower in the ilium without the frontal markers (Table 3).

Discussion

RSA as a tool to measure 3-D movement in the SI joint has been used in a limited number of studies [16–20], but none

Table 2. Accuracy of the phantom

Direction	Accuracy	SD	95% CI
Rotations			
X	-0.025°	0.128	$(-0.106-0.056)$
Y	0.051°	0.039	$(0.026-0.076)$
Z	0.003°	0.021	$(-0.011-0.016)$
Translations			
X	-0.003 mm	0.042	$(-0.024-0.018)$
Y	-0.012 mm	0.028	$(-0.027-0.003)$
Z	0.065 mm	0.023	$(0.016-0.115)$

Accuracy = mean of the difference between true value and measured value; SD = standard deviation of the difference between true value and measured value; 95% CI = 95% confidence interval for accuracy.

Table 3. Limit of significance in the phantom with different marker distributions and in patients before and after the frontal markers were removed

Model	Number of examinations	X Rot	Y Rot	Z Rot	X Trans	Y Trans	Z Trans	ME sacrum	ME ilium	CN sacrum	CN ilium	Markers in sacrum	Markers in ilium
Phantom model													
With frontal markers (MS ABCD)	10	0.06	0.25	0.11	0.08	0.03	0.16	0.04 (0.01)	0.08 (0.02)	17	29	8	8
Without frontal markers (MS ACD)	10	0.19	0.18	0.22	0.18	0.09	0.23	0.04 (0.01)	0.02 (0.01)	17	92	8	5
p values (MS ABCD versus MS ACD)		0.254	0.801	0.010	0.003	0.284	0.313		< 0.001				
Without cranial sacral markers (MS ABC)	10	0.09	0.22	0.22	0.24	0.07	0.18	0.02 (0.01)	0.08 (0.02)	43	29	5	8
p values (MS ABCD versus MS ABC)		0.077	0.568	0.023	0.005	0.067	0.876	< 0.001					
With 3 random markers in each segment	10	0.24	0.26	0.14	0.11	0.09	0.21	0.02 (0.01)	0.01 (0.01)	59	117	3	3
p values (MS ABCD versus MS circles)		0.053	0.457	0.191	0.140	0.016	0.013	< 0.001	< 0.001				
Patients													
With frontal markers (n = 17)	17	0.71	0.24	0.28	0.47	0.28	0.38	0.09 (0.04)	0.13 (0.07)	27 (24)	43 (15)	6.4 (1.3)	5.6 (1.3)
Before removing markers in the symphysis	11	0.52	0.21	0.18	0.15	0.30	0.39	0.08 (0.02)	0.12 (0.05)	20 (8)	38 (9)	6.8 (1.4)	6.8 (1.3)
After removing markers in the symphysis	11	0.55	0.40	0.14	0.14	0.23	0.45	(0.08) (0.02)	0.08 (0.05)	20 (8)	96 (28)	6.8 (1.4)	4.3 (1.3)
p values (patients with versus without frontal markers)		0.213	0.248	0.249	0.592	0.811	0.711	0.341	0.048		< 0.001		< 0.001

Precision expressed as limit of significance = $\text{Mean}_{\text{of the absolute values}} + t_{(n-1)0.005} \times \text{SD}_{\text{of the absolute values}}$; ME = mean error of rigid body fittings; CN = condition number; Rot = rotation; Trans = translation.

Fig. 3 A graph shows the accuracy in setups with different marker distributions. The accuracy is presented as the mean difference between the true value and the measurement obtained by RSA. Trans = translation (mm); Rot = rotation (°).

of these has assessed the accuracy and precision of the method in an experimental setting, as in the current study. We therefore (1) measured the accuracy, precision, and CNs of pelvic RSA with different marker distributions in a phantom model, (2) explored whether frontal markers around the symphysis improve the CN and precision and whether it is possible to avoid markers in the cranial part of the sacrum, and (3) compared the precision obtained by a phantom with the precision obtained by double examinations in patients.

We acknowledge limitations to our study. First, precision from phantom studies cannot be extrapolated to clinical data. Obviously, a phantom is the best tool to evaluate the accuracy of RSA as it ensured standardization and reproducible conditions for the test. However, these results cannot be transferred directly to the analyses of patients. When the 3-D position of each marker is calculated, the soft tissue is an important factor that can disturb x-rays and the markers probably are not as stable in patients as in a phantom. These factors make measurements less accurate and less precise. In patient series, therefore, precision always should be determined by double examination. Second, a potential source of error in our model is that the actual movement of interest exceeds ROM in our phantom. All clinical RSA studies describe small movements in the SI joint [5, 16–20]. In these studies, a

maximum rotation of 3.6° is seen and the translation never exceeds 2 mm. Our displacement protocol included a range of 0 to 5 mm for translations and 0° to 5° for rotation and therefore should cover the normal and potentially pathologic interval of movement. Third, we used a micrometer as a gold standard or true value. This micrometer has a resolution of 0.04° and 0.01 mm. The accuracy was less than 0.07 mm for translation and 0.05° for rotation, and to conclude that this is an actual bias (systematic error), the resolution should have been better. The bias measured in our study is small, and can be explained by the resolution of the micrometer. There is no other logical explanation for the bias and in our opinion, based on our results, no correction of the measurements should be done.

The accuracy of the RSA method depends on the marker distribution (CN) and stability of the markers (precision of calculating the 3-D positions of individual markers) [21]. In the phantom experiment, the markers are inserted and glued to the pelvis and become 100% stable. When the precision of each marker is high, a phantom experiment is useful to calculate CN and highest possible precision for different marker distributions. In the phantom a CN never exceeded 117, and no more than three markers were needed in each segment to achieve this. With eight markers in each segment, the accuracy was less than 0.07 mm in all directions for translation and 0.05° for rotations. There were some minor differences between the different marker distributions, but we found no systematic error that influenced our measurements. The precision was less than 0.16 mm for translations and less than 0.25° for rotations, and these results are comparable to precision measured in pelvic phantoms by others (Table 4) [19, 20]. The phantom experiments qualify pelvic RSA as a proper tool for analysis of 3-D movement in the SI joint, but they do not provide a prediction of precision in a clinical situation where stability of the markers is different. With frontal markers around the symphysis, the CN was 29 in the ilium, but the CN was never greater than 117 using dorsal markers only. The ME was reduced when the frontal markers were removed. Different marker distributions showed some differences, but these differences were extremely small. In all setups, the precision never exceeded a LOS of 0.24 mm for translations and 0.26° for rotations. The use of frontal markers was an easy way to decrease the CN, but this study does not take the biomechanical properties of the ilium and the pubic bone into consideration. Possible plasticity of the iliac and pubic bones can disqualify the use of frontal markers, but that is beyond the scope of this study. When three markers were used, the CN was 117 in the ilium. This is not optimal [21]. However, the accuracy and precision were almost as good as when eight markers were used. We therefore conclude, as long as the markers in the dorsal aspects of the ilium are placed

Table 4. Precision in evaluable studies

Study	Precision						Markers in each segment	CN Sacrum/Ilium	ME sacrum/ilium
	X Rot	Y Rot	Z Rot	X Trans	Y Trans	Z Trans			
Sturesson et al. [16–19]									
20 double examinations in phantom	0.3	0.4	0.1	0.2	0.2	0.1	> 4	NR	NR
Tullberg et al. [20]									
10 double examinations in patients	1.0	1.4	1.1	0.2	0.2	0.5	6	NR	NR
Current study									
Phantom	0.1	0.3	0.1	0.1	0.1	0.2	8	17/29	0.04/0.08
Patients	0.7	0.2	0.3	0.5	0.3	0.4	6	27/43	0.09/0.13

Precision expressed by $t_{(n-1)0.005} \times SD$ of the difference between the two examinations; CN = condition number; ME = mean error of rigid body fittings; NR = not reported; Rot = rotation; Trans = translation.

with the best spread possible, there is no need for frontal markers.

In the initial patients, we found that sacral markers, especially the cranial ones, were hard to get into the bone and often ended up in the soft tissue. This probably is attributable to the strong dorsal ligaments covering the sacrum. CT scans performed to evaluate the quality of the SI joint arthrodesis documented this. When these cranial markers were excluded in the phantom, the CN ranged from 17 to 43, which is acceptable. Without these markers, there were reductions in accuracy in the Y translation and in precision of the Z rotation and X translation. As in the evaluation of the frontal markers, these differences were small, and the precision was good without these markers. Precision was better in the phantom than in the patients. In the patients, the precision of the rotations had a LOS less than 0.7° in all directions, and for translation the precision was less than 0.5 mm (Table 3). These values were comparable to precision measurements by others (Table 4) [19, 20]. The RSA method has been widely used in the study of hip prostheses. Using double examinations, precision was reportedly between 50 and 150 μm [2]. When RSA is used in the SI joint, the segments are large and the distance between the segments (sacrum and ilium) is larger than in analysis of implants. The ME also tended to be larger in the patients with frontal markers, and all these factors might have a negative influence on the precision [9]. Abdominal and pelvic soft tissue also might decrease the quality of marker observation on the radiograph and these factors probably explain why our results are somewhat poorer. Furthermore, zero motion between two examinations cannot be expected. As the patients were allowed to move between the examinations, it is possible that the joints might align differently between the two examinations. Therefore, when precision in patients is evaluated, the joint alignment must be taken into consideration. It was difficult to obtain a proper CN in patients when the frontal markers

were removed. All examinations that were excluded had less than four stable markers in the ilium. It seems that four markers with a good spread is enough to obtain good precision, however, we recommend putting more than four markers in the dorsal aspects of the ilium to ensure that no examination ends up being excluded. This is important, especially in patients with implants, where markers can be hidden by the implant.

Our data suggest RSA is a reasonable method to measure SI joint movement in patients. The accuracy was high and we identified no systematic error in the phantom study that would require correction. Precision was high in the phantom and as long as the CN was less than 120 and the ME less than 0.35, we found no need for more than three to four properly placed markers in the back of the pelvis to measure SI joint movement. In patients however, we recommend more than four markers in each segment to ensure an appropriate segment for the analysis. The use of frontal markers did not improve precision, and therefore are not needed.

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