A New CT Based Method for Post-operative Motion Analysis of Pelvic Fractures

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Received: 28 November 2018 / Revised: 5 January 2019 / Accepted: 9 January 2019 / Published online: 29 January 2019
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Abstract Conventional X-ray is commonly used for pelvic fracture follow-ups, but has a precision of only ± 5 mm. Implantation of tantalum beads together with RSA has shown high precision but not applicable in clinical practice. CT scan has been shown a suitable substitute for RSA to follow the metal markers. We aimed to assess whether implantation of metal markers could be avoided using CT scan and merging of bone surface anatomy. A human cadaveric pelvis marked with 0.8 mm tantalum beads was fixed over the symphysis and the right SI-joint. Left hemipelvis was subsequently distracted using plastic spacers. Sequential CT exams was conducted and data were analyzed using Sectra[®] (Sectra AB), CTMA package. Examinations were repeated after 2 weeks. Bone registration showed better precision than registration based on tantalum beads. However, only the difference in angular changes was statistically significant ($p = 0.008$). The confidence interval of the

repeatability was ± 0.5 mm for translation and $\pm 0.5^\circ$ for rotation. This new non-invasive technique showed good precision and repeatability and might be a future option in clinical practice for post-operative follow-ups of patients with pelvic fractures.

Keywords Pelvic bone · Pelvic fracture · Pelvic imaging · CT volume fusion · CT motion analysis

1 Introduction

By tradition, conventional X-rays have been used for evaluating the post-operative outcome and for the follow-up of pelvic fractures. However, previous studies using plain radiographs have shown poor inter- and intra-observer reliability, a low level of reproducibility and a measurement error of at least ± 5 mm [3, 4, 11]. Introduction of Computed Tomography (CT) has added to better understanding of the fractures pre-operative and better description of post-operative radiological outcome [1]. As an alternative the Radiostereometric Analysis (RSA) technique has been encouraged because of its accuracy and precision for fracture follow-ups, but the technique is cumbersome to use in clinical settings and demands additional implants (tantalum beads) [3, 22].

A new promising method using CT examinations and volume registration in conjunction with mathematical routines was introduced by Olivecrona et al.

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[13]. This image post-processing method addresses how two rigid bodies shifts position relative to each other using volume registration. Movements are expressed at the geometrical center of the moving object and/or at any arbitrary user defined points of interest, such as an orthopedic implant or a fracture line. This technique has been shown to be accurate, precise, reliable and repeatable in several studies on hip arthroplasty models and in hip arthroplasty patients [5–7, 9, 13–19].

The aim of this study was to validate a new CT based migration method in a human pelvic fracture model bone using distraction levels below the precision limitation of X-ray (± 5 mm), and to evaluate whether implantation of tantalum beads could be avoided.

2 Materials and Methods

A denuded human pelvic bone that has previously been used for educational purposes at the department was used. The right SI-joint was immobilized using a 3.5 mm cortical screw (DePuy/Synthes, West Chester, USA). An anterior symphyseal plate (DePuy/Synthes, West Chester, USA) was applied over the symphysis with 3 cortical screws on each side. The screws on the left side of the symphysis were backed two revolutions to allow some gap for consequent placement of plastic spacers either in the symphysis or in the left SI-joint. The model was marked with 0.8 mm diameter tantalum beads, two on each side of the symphysis pubis (apical and caudal) and in the same manner four beads was placed anteriorly on the superior and inferior margin of the left SI-joint. The right and left sides of the pelvis were further marked with tantalum beads in each acetabulum and over the superior margin of each iliac wing (totally six beads on right side and six beads on the left side and two beads over the left side of the sacrum in agreement with Solomon et al. [22] (Fig. 1).

CT examinations were acquired using a clinical CT scanner (Toshiba Aquilion ONE, Toshiba Medical Systems, Tochigi-ken, Japan). SEMAR (single-energy metal artefact reduction) was used to reduce artefact effect. Low dose CT-scanning with 137 kV and 0.5 mm thick slices was conducted.

Before each CT examination, the distance between two tantalum beads over the superior portion of the anterior symphysis pubis and two tantalum beads over

Fig. 1 Human pelvis used in this study. The pelvis is fixed with Osteosynthesis in the front and over the right SI-joint. The left SI-joint is expandable. Tantalum beads are implanted over the right and left iliac wings, over both acetabulum and over the symphysis and the left SI-joint

superior portion of the left SI-joint were measured using Calipers (Cocraft, Clas Ohlson, Stockholm, Sweden, Article Number 40-8745) in order make sure an actual displacement was occurred. The pelvis was always examined in two different positions on the CT bed (position a and b). Between these positions the pelvis was lifted from the CT bed and reoriented to mimic different patient positioning on repeated examinations. Stability of the construct was manually tested before each pair of CT examination. The pelvic sides were displaced in relation to each other by using one, two, and three plastic spacers over the symphysis initially and then over the left SI-joint, again using one, two, and three plastic spacers. This resulted in seven pairs of CT volumes (denominated 1a–7b) where the a- and b-scans represented the same pelvic anatomy but acquired in different position in the scanner. Sectra (Linköping, Sweden) CTMA program was used for analyzing the CT data. We made the assumption that the right side of the pelvis was the stable part of the system and used this as reference during the study and analysis. The sacrum was not regarded as a part of the pelvic sides.

Two experiments comprising volume registration and measurements were performed. In experiment one the volume registration was based on the implanted tantalum markers. In experiment two the registration is based on the bone surface.

Fig. 2 Registration of right and left side of pelvis using bone registration in the left and tantalum registration to the right

Each experiment comprised:

1. Registration of right side of pelvis as stationary object (Fig. 2).
2. Registration of left side of pelvis as moving object (Fig. 2).
3. Designation of two points of interest for expressing the movement of the moving object; one on the left side of the symphysis and one on the iliac side of the left SI-joint.

The registration in experiment 1 used registration between mesh data extracted from the bone surfaces and experiment 2 used mesh data representing the tantalum beads (Fig. 2).

To test repeatability, procedures 1–3 were repeated after 2 weeks.

The CTMA software automatically calculates the shift of position of the moving object relative to the stationary across the two CT volumes. This generates a rotation matrix and a translation matrix. The rotation of a moving rigid object is universal, but the translation varies depending on where in the object this is measured. This can be visualized by rotating the earth around the north–south axis. The rotation is the same for the entire globe but the translation on the surface varies and decreases the farther north or south from the

equator it is measured. Therefore, migration must be expressed at specified points (Fig. 3). Numerical data was expressed and saved in a spreadsheet format in six degrees of freedom (rotations and translations around orthogonal coordinate axes) using Euler decompositions with Tait–Bryant angles with the order of rotation x–y–z in original CT grid coordinates or relative to an arbitrary chosen multi-planar reconstruction coordinate system. Total angle in space of rotation of the moving object along with length of translation vector at any specified point were also expressed.

Precision was defined as “the closeness of agreement between independent test results obtained under same conditions” [20]. To calculate precision, the dual CT-examinations at each displacement level were compared, as, per definition, no movement should occur. Repeatability was defined as “precision under repeatability conditions” [20].

3 Ethics

A question was raised to the Stockholm’s local ethical committee regarding using this human pelvis and answer was received that as this specimen was not

Fig. 3 Automated report on translation over the symphysis, SI-joint and angular change of the left side of the pelvis

Table 1 Positions 1a–7b illustrates different distraction levels. Dual examinations with CT-scan, the same distraction level (a, b) but 2 different positioning of the object (the pelvic model) are used for precision measurement. Angular changes are in Degree. Translational changes are in Millimeter

Bone	Angular deformity	Translation in symphysis	SI-joint translation	Angular deformity X-axis	Angular deformity Y-axis	Angular deformity Z-axis	Translation symphysis X-axis	Translation symphysis Y-axis	Translation symphysis Z-axis	Translation SI-joint X-axis	Translation SI-joint Y-axis	Translation SI-joint Z-axis
	Mean: 0.11 Median: 0.09 CI 0.05–0.17	Mean: 0.15 Median: 0.14 CI 0.07–0.23	Mean: 0.18 Median: 0.18 CI 0.12–0.24	Mean: – 0.004 Median: – 0.01 CI – 0.04 to 0.04	Mean: 0.005 Median: – 0.03 CI – 0.05 to 0.06	Mean: 0.004 Median: 0.013 CI – 0.09 to 0.10	Mean: – 0.005 Median: 0.006 CI – 0.13 to 0.12	Mean: – 0.009 Median: 0.008 CI – 0.10 to 0.08	Mean: – 0.03 Median: – 0.03 CI – 0.09 to 0.04	Mean: – 0.008 Median: 0.004 CI – 0.08 to 0.06	Mean: – 0.02 Median: 0.01 CI – 0.14 to 0.1	Mean: – 0.02 Median: – 0.03 CI – 0.14 to 0.09
<i>(a) Precision measurements using bone registration</i>												
Position												
1a–1b	.040	.062	.077	.024	.035	.013	.032	.052	– .006	.004	.075	– .015
2a–2b	.202	.198	.197	– .050	– .044	.189	– .190	.008	– .054	.062	– .184	– .033
3a–3b	.040	.112	.176	.040	– .025	.013	– .039	.055	– .089	.006	.098	– .146
4a–4b	.088	.285	.269	– .011	.092	.004	.205	– .179	.085	.108	– .194	.153
5a–5b	.148	.136	.181	– .055	.070	– .121	.107	– .082	.019	– .111	– .074	.123
6a–6b	.163	.044	.213	.062	– .064	– .134	.006	– .033	– .029	– .068	.139	– .146
7a–7b	.079	.225	.116	– .039	– .026	.068	– .154	.113	– .117	– .057	.011	– .100
<i>(b) Precision measurements using tantalum registration</i>												
Tantalum	Angular deformity	Translation in symphysis	SI-joint translation	Angular deformity X-axis	Angular deformity Y-axis	Angular deformity Z-axis	Translation symphysis X-axis	Translation symphysis Y-axis	Translation symphysis Z-axis	Translation SI-joint X-axis	Translation SI-joint Y-axis	Translation SI-joint Z-axis
	Mean: 0.23 Median: 0.23 CI 0.18–0.28	Mean: 0.24 Median: 0.21 CI 0.14–0.34	Mean: 0.24 Median: 0.21 CI 0.14–0.34	Mean: – 0.04 Median: – 0.06 CI – 0.14 to 0.05	Mean: – 0.07 Median: – 0.16 CI – 0.25 to 0.14	Mean: – 0.03 Median: 0.01 CI – 0.11 to 0.05	Mean: 0.009 Median: 0.04 CI – 0.14 to 0.16	Mean: – 0.05 Median: 0.017 CI – 0.23 to 0.11	Mean: – 0.03 Median: – 0.07 CI – 0.12 to 0.07	Mean: 0.05 Median: 0.05 CI – 0.08 to 0.18	Mean: – 0.08 Median: – 0.07 CI – 0.24 to 0.08	Mean: – 0.03 Median: – 0.03 CI – 0.14 to 0.08
Position												
1a–1b	.312	.384	.187	.162	.262	.035	.187	– .296	.159	– .096	– .114	.112
2a–2b	.234	.190	.325	– .153	– .167	.061	.041	.171	– .072	.318	– .066	– .028
3a–3b	.172	.147	.110	– .040	– .057	– .159	.105	.047	– .091	.000	.079	– .076
4a–4b	.237	.244	.221	– .066	– .227	– .001	– .187	.050	– .148	.065	– .022	– .210
5a–5b	.172	.128	.161	– .057	– .155	.041	– .125	– .029	.008	.103	– .121	– .023
6a–6b	.293	.381	.449	– .124	– .257	– .065	– .164	– .337	– .069	.052	– .426	– .130
7a–7b	.198	.205	.197	– .014	.138	– .138	.204	.017	– .015	– .090	.125	.124

traceable to an existing physical body, there were no ethical concerns.

4 Statistics

Paired Student *T* test was used for comparison analysis of scale variables with normal distribution. Normality of datasets was tested based on plotting the data and Shapiro–Wilks test. Precision was measured in mean, median and 95% CI of the mean as recommended by the ASTM standard E177-90a [2]. SPSS (IBM SPSS Statistics for Windows, Version 25.0. Armonk, USA) program was used for statistical calculations.

5 Results

5.1 Precision

Results of the precision calculation comparing bone registration versus registration based on tantalum beads are presented in Table 1a, b. In all measurements bone registration showed better precision, however only measurements of angular deformity were significantly different (mean difference -0.12 , CI -0.2 to -0.05 , $p = 0.008$).

5.2 Measurements in Distraction

Translational measurements and angular measurements of the left side of the pelvis following distraction using bone registration versus registration based on tantalum are presented in Table 2a, b. Calipers measurements showed translation of symphysis ranging 0–4 mm (mean 1.4 mm, median 0.9 mm, CI 0.9–1.9 mm). Calipers measurements showed translation of the left SI-joint ranging from 0 to 5 mm (mean 2.6 mm, median 3 mm, CI 1.8–3.4 mm). There were no statistically significant differences between bone registration and tantalum registration to report angular changes or translation at the symphysis or at the SI-joint. Overall confidence interval of mean difference to report translation during distraction was ± 0.2 mm, and for angular changes $\pm 0.2^\circ$ (Table 2a, b).

5.3 Repeatability

Comparison of repeated measurements showed only significant difference between the first and second measurements regarding precision in Z-axis of translation at the symphysis pubis with bone registration with a mean difference of -0.06 mm (CI -0.1 to -0.16 , $p = 0.016$). The overall 95% CI of repeatability between first and second run were ± 0.2 mm while these were not statistically significant.

Measurements in distraction between first and second run showed significant differences between absolute values of translation over the SI-joint using bone registration with a mean difference of 0.08 mm (CI 0.02–0.15, $p = 0.01$), translation in the Z-axis over the SI-joint using tantalum registration with a mean difference of -0.17 mm (CI -0.28 to -0.06 , $p = 0.004$) and translation in the Z-axis over the SI-joint using bone registration with a mean difference of -0.14 mm (CI -0.26 to -0.02 , $p = 0.03$). The overall CI of repeatability for reporting distance changes during distraction for remaining measurements (according to Table 2) were ± 0.5 mm but these were not statistically significant. In all measurements 95% CI of repeatability for reporting rotational changes between the first run and the second run was ± 0.5 degree while these differences were not statistically significant.

6 Discussion

The main finding of our study was that CT examination using bone registration was more precise than registration with tantalum beads. Both techniques were repeatable. Implantation of tantalum beads while using CT examination with motion analysis seems unnecessary.

Orthopedic surgeons traditionally use plain X-rays to report their post-operative results and to monitor healing over time. However, this technique has a reported measurement error of at least ± 5 mm [3, 4, 11]. Still, the most common radiographic outcome measurement technique following pelvic fracture surgery according to the literature is the method presented by Matta and Tornetta using conventional X-rays including pelvic antero-posterior (AP), inlet and outlet views. In this method the distance in the SI-joint and the symphysis is reported. The maximum reported distance in any plane is

Table 2 1A–7A represents different distraction levels of the left side of the pelvis. Angular changes are in Degree. Translational changes are in Millimeter

Tantalum	Angular deformity	Translation in symphysis	SI-joint translation	Angular deformity X-axis	Angular deformity Y-axis	Angular deformity Z-axis	Translation symphysis X-axis	Translation symphysis Y-axis	Translation symphysis Z-axis	Translation SI-joint X-axis	Translation SI-joint Y-axis	Translation SI-joint Z-axis
Mean:	5.9	Mean: 1.8	Mean: 3.5	Mean: 0.9	Mean: 1.5	Mean: 0.2	Mean: 0	Mean: 0.1	Mean: 0	Mean: 1.2	Mean: 1.2	Mean: 1.2
Median:	4.6	Median: 1.3	Median: 3.2	Median: 1.7	Median: 0.3	Median: 0.2	Median: 0	Median: 0.1	Median: 0	Median: 1.1	Median: 1.1	Median: 1.1
CI	3.9–7.8	CI 1.1–2.5	CI 2.7–4.3	CI 0.2 to 2.2	CI 0.7 to 2.2	CI 1.7 to 2.2	CI 1.2 to 0.3	CI 0.6 to 0.8	CI 0.3 to 0.3	CI 0.3–2.2	CI 0.5–1.9	CI 2.6 to 1.2
(a) Measurement of angular changes with tantalum registration of left side of the pelvis with respect to right side of the pelvis including translational changes over the symphysis and the left SI-joint												
1A–2A	.285	.107	.172	.142	.108	.221	-.042	-.081	-.055	.063	-.006	-.160
1A–3A	.5121	.837	2.228	2.172	2.717	3.811	.771	.295	-.139	1.531	1.118	1.171
1A–4A	12.832	4.003	3.963	5.419	7.157	9.526	2.544	2.834	1.234	3.635	1.523	1.422
1A–5A	2.049	.530	3.013	2.035	-.160	.179	.110	-.503	.126	.511	1.927	2.259
1A–6A	2.542	.261	3.228	2.084	.318	1.427	.074	-.118	-.220	1.225	1.814	2.373
1A–7A	4.609	1.284	7.171	2.302	-.3915	.707	-.1153	.561	-.076	4.495	2.994	4.717
2A–3A	4.671	.805	1.933	2.473	2.450	3.168	.651	.271	-.388	1.146	.895	1.274
2A–4A	12.264	3.573	3.624	6.470	6.575	8.474	2.473	2.526	.520	3.195	1.382	1.008
2A–5A	1.774	.464	2.741	1.697	-.356	-.379	-.033	-.457	-.071	-.022	1.721	2.133
2A–6A	2.111	.347	3.224	1.960	-.048	.782	.036	.138	-.316	.856	1.884	2.472
2A–7A	4.504	1.318	6.776	1.745	-.4149	.121	1.092	.732	-.094	3.758	2.558	5.025
3A–4A	7.623	3.776	3.078	3.128	4.530	5.400	1.848	3.026	1.298	2.052	2.241	.490
3A–5A	4.615	1.283	1.726	-.027	-.2969	-.3532	-.815	-.874	.467	1.234	.787	-.915
3A–6A	3.450	.829	1.333	-.016	-.2436	-.2443	-.718	-.366	.195	-.421	.802	-.978
3A–7A	7.512	1.986	4.845	.115	-.6904	-.2968	1.974	.101	.196	2.931	1.636	3.493
4A–5A	12.140	3.413	4.601	-.5215	-.8283	-.6825	2.345	2.363	-.754	3.007	3.260	1.224
4A–6A	10.882	4.117	4.348	-.3.176	-.7.811	-.6.672	2.833	2.790	1.069	3.093	3.986	1.492
4A–7A	14.544	5.377	5.706	-.2.937	12.264	6.954	4.229	3.239	-.731	-.073	.154	4.082
5A–6A	1.384	.689	.987	.250	.472	1.278	.054	.657	-.200	.957	.786	1.186
5A–7A	4.021	1.735	4.910	.143	-.3.955	.707	1.376	1.056	.019	3.993	.603	2.747
6A–7A	4.363	1.369	3.901	-.485	-.4.272	-.726	1.239	.573	.106	2.687	-.603	2.763

Table 2 continued

Bone	Angular deformity	Translation in symphysis	SI-joint translation	Angular deformity X-axis	Angular deformity Y-axis	Angular deformity Z-axis	Translation symphysis X-axis	Translation symphysis Y-axis	Translation symphysis Z-axis	Translation SI-joint X-axis	Translation SI-joint Y-axis	Translation SI-joint Z-axis
	Mean: 5.8	Mean: 1.8	Mean: 3.5	Mean: 1	Mean: -1.5	Mean: 0.2	Mean: -0.3	Mean: 0.1	Mean: 0	Mean: 1.2	Mean: 1.3	Mean: -1.9
	Median: 4.6	Median: 1	Median: 3.4	Median: 1.6	Median: -0.5	Median: 0.2	Median: -0.3	Median: 0.4	Median: -0.1	Median: 1.1	Median: 1.3	Median: -1.5
CI	3.9–7.8	CI 1–2.4	CI 2.7–4.3	CI -0.2 to 2.2	CI -3.7 to 0.7	CI -1.9 to 2.2	CI -1 to 0.4	CI -0.6 to 0.9	CI -0.3 to 0.3	CI 0.3–2.2	CI 0.6–2	CI -2.6 to -1.2

(b) Measurement of angular changes with tantalum registration of left side of the pelvis with respect to right side of the pelvis including translational changes over the symphysis and the left SI-joint

1A–2A	.441	.354	.194	.292	.271	.188	.253	-.126	.213	.116	.155	.019
1A–3A	5.086	1.024	2.236	2.125	2.810	3.721	.913	.395	-.243	1.458	1.211	-1.185
1A–4A	12.739	4.052	3.839	5.521	7.069	9.404	2.511	-2.814	1.484	3.592	-1.307	-.354
1A–5A	2.097	.656	3.074	2.096	-.105	.040	-.005	-.656	.032	.171	1.914	-2.400
1A–6A	2.565	.597	3.367	2.210	.437	1.236	.593	-.023	.064	1.385	2.161	-2.180
1A–7A	4.316	1.009	7.080	2.164	-3.708	.378	-.586	.814	-.110	4.443	3.244	-4.457
2A–3A	4.603	.851	2.055	2.443	2.382	3.142	.545	.408	-.512	1.093	1.015	-1.414
2A–4A	12.431	3.817	3.687	6.604	6.608	8.549	2.608	-2.696	.705	3.271	-1.456	-.880
2A–5A	1.734	.365	2.903	1.644	-.457	-.317	-.310	-.161	-.108	-.119	1.914	-2.179
2A–6A	2.256	.237	3.160	2.031	.034	.982	.021	.144	-.187	1.028	1.835	-2.359
2A–7A	4.573	1.054	6.882	1.857	-4.180	.004	-.905	.539	-.022	3.849	2.564	-5.097
3A–4A	7.714	3.584	3.325	3.132	4.319	5.693	1.488	-3.058	1.132	2.328	-2.370	.141
3A–5A	4.705	1.156	1.797	-.079	-2.949	-3.664	-.724	-.774	.460	-1.319	.883	-.843
3A–6A	3.326	.884	1.328	.120	-2.515	-2.176	-.712	-.430	-.301	-.025	.778	-1.076
3A–7A	7.329	1.561	4.766	.148	-6.542	-3.310	-1.469	.499	.175	2.627	2.223	-3.297
4A–5A	12.353	3.699	4.642	-5.347	-8.527	-6.788	-2.650	2.444	-.831	-3.063	3.208	-1.370
4A–6A	10.893	4.098	4.397	-3.141	-7.833	-6.683	-2.779	2.817	-1.068	-2.603	3.165	-1.545
4A–7A	14.501	4.802	5.772	-2.861	-11.919	-7.471	-3.514	3.149	-.892	-.329	4.189	-3.958
5A–6A	1.477	.441	1.164	.355	.493	1.348	.191	.386	-.092	1.148	-.040	-.183
5A–7A	3.661	1.575	4.905	.123	-3.638	.393	-.769	1.360	-.199	3.896	1.261	-2.700
6A–7A	4.253	1.135	3.745	-.515	-4.098	-.999	-.862	.730	.116	2.578	.930	-2.552

graded as excellent if it is under 4 mm, as good if the distance is under 10 mm, as fair if the distance is between 10 and 20 mm and if any measurement is over 20 mm the result is considered as poor [10]. However, Matta and Tornetta's technique has been criticized because of lack of reproducibility as finding anatomical landmarks between two observers or two separate examinations has been shown difficult [8]. We applied a modified Matta and Tornetta technique as we used distance changes at the symphysis pubis and at the SI-Joint when comparing a point to its previous position. Our results showed that appropriate imaging modality together with appropriate automated interpretations technique minimizes the level of uncertainty and might contribute to better precision and accuracy with a method that can be used in a clinical setting. The distance changes for each point is automatically reportable with respect to its previous position in a 3D manner and not with respect to the contralateral side. Automatic merging of 3D CT generated volumes, with a precision of ± 0.2 mm for translation and $\pm 0.2^\circ$ for rotation reduces the risk of observer induced measurement bias. Further, reporting angular deformity of unstable parts of the pelvis, which has been difficult previously, is possible with this technique [12]. Other measurement techniques with higher precision, such as RSA, have been proposed as an alternative to plain X-rays. RSA technique has been used in fracture research. Solomon et al. studied tibia plateau fractures using RSA technique and found that implantation of 6 tantalum beads in each fragment section was sufficient. The authors showed promising results to report deformity over time with a reported precision of ± 0.05 mm for translation and $\pm 0.2^\circ$ of rotation [22]. The authors concluded that RSA technique, because of its precision and accuracy justifies implantation of tantalum beads in fracture surgery research [22]. The technique is however invasive and cumbersome and demands implantation of tantalum beads around the fracture and is not feasible to conduct in daily practice [3].

Olivecrona et al. have previously studied CTMA extensively as explained before. The authors were able to show that using CT-examination and fusion of the volumes on hip replacements, tantalum beads were as traceable as RSA and the technique was not inferior to RSA [13].

Bone registration showed superior results compared to registration with metal markers. This might reflect the fact that using entire meshed surface of the

bone is superior to use outspread points (metal markers), as the numbers of metal markers are limited.

Concerns about increased radiation doses for CT scans compared to conventional X-rays have been raised. However, low-dose CT scan using volume fusion technique has been shown possible with radiation dosage as low as 0.7 mSv, which is comparable to conventional X-rays [21].

The major strength of our study was its novelty when introducing a new technique that might be feasible for clinicians to use in daily practice when reporting their outcome over time. A non-invasive method with a precision better than 1 mm for translation and one degree for rotation would improve the ability to monitor and better understand how to manage these often complex fractures. We had several limitations in our study. One obvious limitation was its model character. The human pelvic model we used was without soft tissue, spinal column and femurs. We used only six metal markers over each side of the pelvis, as proposed by Solomon et al. [22], the question remains whether implantation of more tantalum beads could improve precision of volume registration using tantalum beads. Radiation dosage using CT scan is another issue implementing this technique in daily practice. However, implementing protocols for low dose CT scan in collaboration with radiology department and application of SEMAR would be practical options.

7 Conclusion

This new non-invasive technique showed good precision and repeatability and might be a future option in clinical practice for post-operative follow-ups of patients with pelvic fractures. Future clinical in vivo studies are encouraged to further study its practical application and advantages in comparison to conventional X-rays. Implantation of tantalum beads while using 3D CT with merging of the volumes seems unnecessary.

Author's Contribution LW and AE designed the study and contributed to manuscript writing. HE has long experience of volume registration using CT-scan and contributed to examination, calculations and manuscript writing. PB has participated in design of the study and writing the final manuscript.

Compliance with Ethical Standards

Conflict of interest The authors report no conflict of interest. PE and HO have consultant duties with Sectra®.

Data availability All data would be available on request.

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