Received: 19 December 2022 | Revised: 3 February 2023 | Accepted: 1 March 2023

DOI: 10.1002/jor.25547

RESEARCH ARTICLE

Journal of Orthopaedic Research®

Statistical shape modeling of the large acetabular defect in hip revision surgery

Sara De Angelis[1] | Johann Henckel[2] | Sean Bergiers[1] | Harry Hothi[2,3] | Anna Di Laura[2,3] | Alister Hart[1,2,4]

[1]Institute of Orthopaedics and Musculoskeletal Science, University College London, London, UK

[2]Royal National Orthopaedic Hospital NHS Trust, Stanmore, UK

[3]Department of Mechanical Engineering, University College London, London, UK

[4]Cleveland Clinic, London, UK

Correspondence
Alister Hart, Institute of Orthopaedics and Musculoskeletal Science, University College London, London, UK.
Email: a.hart@ucl.ac.uk

Abstract

The assessment of three-dimensional bony defects is important to inform the surgical planning of hip reconstruction. Mirroring of the contralateral side has been previously used to measure the hip center of rotation (CoR). However, the contralateral side may not be useful when diseased or replaced. Statistical Shape Models (SSMs) can aid reconstruction of patient anatomy. Previous studies have been limited to computational models only or small patient cohorts. We used SSM as a tool to help derive landmarks that are often absent in hip joints of patients with large acetabular defects. Our aim was to compare the reconstructed pelvis with patients who have previously undergone hip revision. This retrospective cohort study involved 38 patients with Paprosky type IIIB defects. An SSM was built on 50 healthy pelvises and used to virtually reconstruct the native pelvic morphology for all cases. The outcome measures were the difference in CoR for (1) SSM versus diseased hip, (2) SSM versus plan, and (3) SSM versus contralateral healthy hip. The median differences in CoR were 31.17 mm (interquartile range [IQR]: 43.80–19.87 mm), 8.53 mm (IQR: 12.76–5.74 mm), and 7.84 mm (IQR: 10.13–5.13 mm), respectively. No statistical difference ($p > 0.05$) was found between the SSM versus plan and the SSM versus contralateral CoRs. Our findings show that the SSM model can be used to reconstruct the absent bony landmarks of patients with significant lysis regardless of the defect severity, hence aiding the surgical planning of hip reconstruction and implant design.

KEYWORDS

custom implants, hip reconstruction surgery, Paprosky IIIB defects, statistical shape modeling

1 | INTRODUCTION

Total hip arthroplasty (THA) is a widespread orthopedic procedure used to restore hip joint function when severe acetabular defects are present.[1] The management of severe acetabular bone loss is a challenging task in revision THA. Multiple treatment options have been proposed such as porous tantalum acetabular components with or without structural allograft or metal augments,[2,3] standard cage reconstruction with iliac or ischial screw fixation,[3,4] and cup-cage constructs.[5] However, these techniques often come with unsatisfactory results and present a high revision rate due to implant failure.[6] Custom-made acetabular implants can overcome these challenges by fitting the implant to the residual host bone, playing a crucial role in complex reconstruction surgery.[7]

The use of preoperative planning and patient specific instrumentation allows for an accurate positioning of the acetabular components for a better performance, reducing the need for revision surgery.[8,9] Mirroring of the healthy contralateral hemipelvis has been previously used to measure the hip center of rotation (CoR).[9] However, this technique is affected by human anatomy asymmetry and cannot be applied when the contralateral hemipelvis is pathological or metal work is present.[10]

Literature shows how pelvic Statistical Shape Models (SSMs) have mainly been used for automatic bone segmentation purposes[11–13] and also to reconstruct pelvic bone defects,[14–16] however, these studies were limited to computational models only (no patients involved) or patient cohorts as small as two or eight patients.[15,16]

We aimed to better understand whether SSM could be used to aid the reconstruction of important bony landmarks that are absent in hip joints of patients with large acetabular defects. Our objective was to compare the CoR of the SSM with patients who had previously undergone hip revision surgery for large acetabular defects planned without the SSM technique.

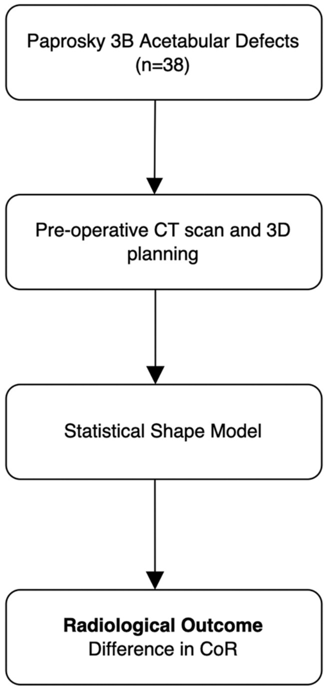

FIGURE 1 Flowchart of the study design. CoR, center of rotation.

2 | MATERIALS AND METHODS

2.1 | Study design and outcome measures

This was a retrospective cohort study involving 38 patients with Paprosky type IIIB defects. Type III acetabular defects present a major destruction of the acetabular rim and the teardrop. They also show severe lysis of the ischium, resulting in superomedial component migration.[1] An SSM was trained on the basis of 50 healthy pelvises and was used to virtually reconstruct the native pelvic morphology for all 38 cases. Within the cohort, 18 of the 38 patients had healthy contralateral sides. The SSM was then compared with the preoperative computerized tomography (CT)-based plan for all patients whose surgery was planned without the SSM technique. Study design is shown in Figure 1.

Our main outcome measure was the difference in CoR between the following groups: (1) SSM versus diseased hip, (2) SSM versus plan, and (3) SSM versus contralateral healthy hip.

2.2 | Data preparation

2.2.1 | Training set

The training set used to construct the SSM consisted of 50 pelvic CT scans of patients without bony abnormalities. The model set consisted of 50 male hemipelvises and 50 female hemipelvises. The scans were automatically segmented in Simpleware ScanIP Medical (Version 2022.3; Synopsys Inc.), and a three-dimensional (3D) reconstruction was generated for each hemipelvis.

2.2.2 | Test set

The test set consisted of 38 patients with Paprosky IIIB defects, 18 females and 10 males. Their mean age was 69 years (standard deviation [SD] = 10.64). Their preoperative CT scans were segmented using the same software by mean of a combination of manual and automatic segmentation tools. The 3D virtual plans of the 38 cases were used to test the statistical model, and the contralateral hemipelvises of patients that did not present an implant were investigated. Out of the 38 patients, 2 did not undergo revision surgery and only the virtual plan was available.

2.2.3 | Validation set

Ten healthy hemipelvises formed the validation set. Five females and five males were selected from the training set and used to validate the virtual reconstruction process.

2.3 | SSM

The 50 pelvises that formed the training set were initially aligned to ensure a fixed pose of the data set. A mean shape of the hemipelvis was then registered to each individual hemipelvis using a point mapping technique. The mean shape served as the reference object and provided the locations for the points to be mapped. Principal component analysis was applied on the data set to investigate the correlations between the mean shape and the model set using three modes of variation. Assuming that the healthy parts of the diseased hips that formed the test set could predict the shape of the anatomy, the acetabulum was removed and the remaining parts were used to build the SSM. The healthy parts of the diseased hip were aligned to the best fit model which was generated from the mean shape and the dense data points of the individual geometries.

2.4 | Image analysis

The CoR of the SSM was calculated using a sphere matching technique.[17,18] The same method was used to compute the CoR of the diseased hip, the plan and the healthy contralateral side. First, the difference in CoR between each diseased hip and its respective SSM was calculated to quantify the severity of the defect. Second, the difference in CoR between the SSM and the plan was computed. Lastly, the difference in CoR between the contralateral healthy side and the SSM was calculated. To provide *XYZ* interpatient relevance, the coordinate system was changed with respect to the anterior pelvic plane (APP) using the anatomical definitions.[19] The APP was defined using three points: (1) the right anterior superior iliac spine, (2) the left anterior superior iliac spine, and (3) the pubic tubercle. Using these reference points, the plane was created and the centroid distances were calculated. *X* corresponded to the sagittal plane, *Y* to the axial plane, and *Z* to the coronal one.

2.4.1 | Statistical analysis

Statistical analysis was performed using GraphPad Prism (version 9.1; GraphPad Software) to investigate statistical significance between the groups. Normal distribution of the data was checked by means of the D'Agostino normality test for each group. The data were determined to be nonnormally distributed. A Mann–Whitney *U* test for nonparametric independent values was carried out. The significance level was set at $p < 0.05$.

2.5 | Validation

The SSM built using the training set was used to virtually reconstruct the hemipelvises of 10 healthy patients. Their CoR was measured using the sphere matching technique described in Section 2.3.[17,18] The difference in CoR with respect to their corresponding SSM was calculated to test the performance of the model.

3 | RESULTS

The image analysis and validation results are reported. We present the discrepancy in CoR between the diseased hip and the SSM, the plan and the SSM, and the healthy contralateral side and the SSM.

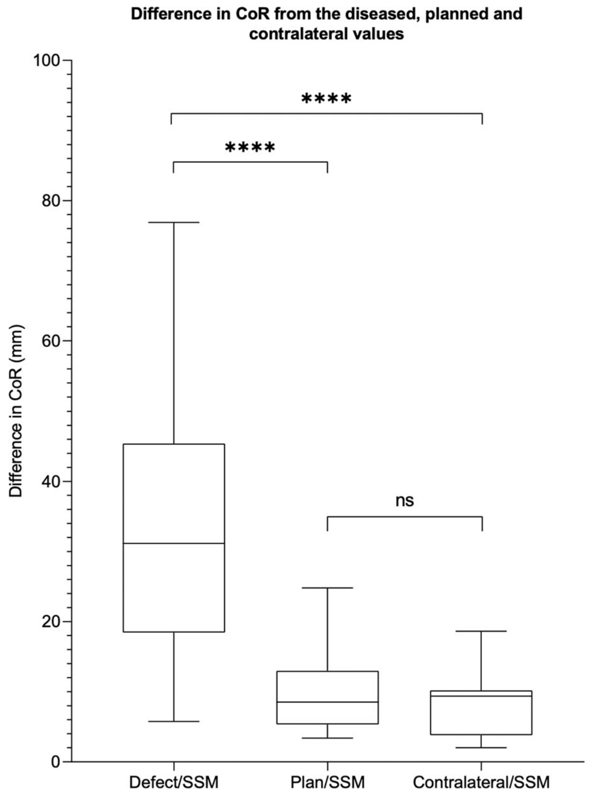

FIGURE 2 Center of rotation (CoR), expressed as differences between the Statistical Shape Model (SSM) and the diseased, planned, and contralateral values.

The discrepancy in CoR between the healthy hip and the SSM was used to validate the model.

The largest difference in CoR was found between the 38 diseased hips and their corresponding SSMs, with a median of 31.17 mm (interquartile range [IQR]: 43.80–19.87 mm). The median difference in CoR between the plan and the SSM was 8.53 mm (IQR: 12.76–5.74 mm). In seven cases, the surgeon chose a high CoR to maximize bony fixation. The median difference in CoR between the SSM and the healthy contralateral side was 7.84 mm (IQR: 10.13–5.13 mm). The results are shown in Figure 2.

An average case corresponding to each group for which the analysis was carried out is illustrated in Figures 3, 4, and 5, respectively. Figures 6–8 show cases of patients that reported a significant change in *X*, *Y*, and *Z* for the defect versus SSM comparison. The axial displacement in CoR was found to be the largest for defect versus SSM in the *X*, *Y*, and *Z* direction.

The median difference in CoR was 13.13 mm (IQR: 17.31–5.62 mm) for *X*, 18.96 mm (IQR: 33.85–10.90 mm) for *Y*, and 12.91 mm (IQR: 23.19–5.14 mm) for *Z*. The sagittal displacement in CoR was the largest for plan versus SSM in the *X*, *Y*, and *Z* direction. The median difference in CoR was 5.17 mm (IQR: 7.76–2.94 mm) for *X*, 3.90 mm (SD = 4.75–1.81 mm) for *Y*, and 4.59 mm (IQR: 7.23–2.84 mm) for *Z*. The sagittal displacement in

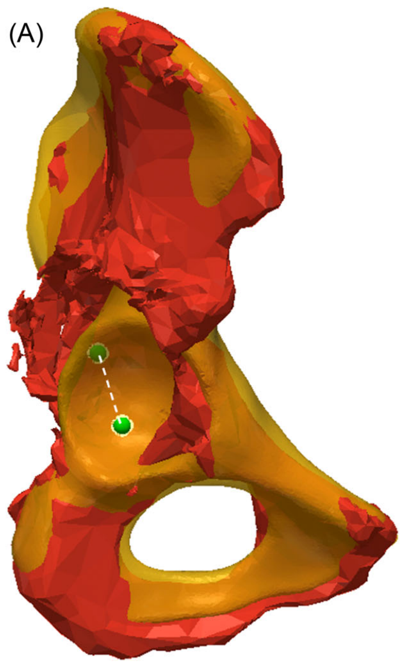

FIGURE 3 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the diseased hip. [Color figure can be viewed at wileyonlinelibrary.com]

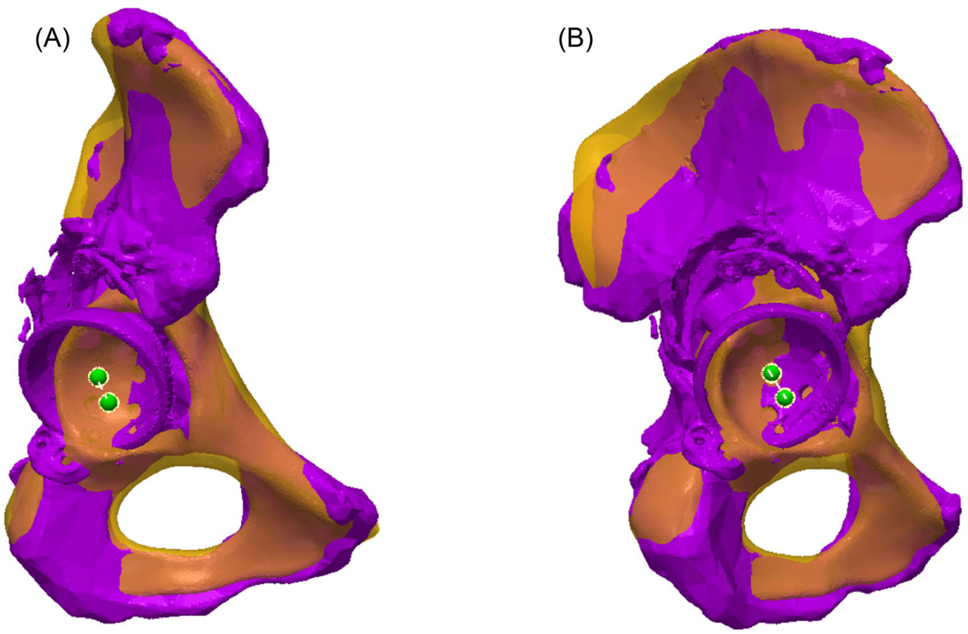

FIGURE 4 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the plan. [Color figure can be viewed at wileyonlinelibrary.com]

CoR was the largest for contralateral versus SSM in the *X*, *Y*, and *Z* direction. The median difference in CoR was 6.20 mm (SD = 9.7–3.36 mm) for *X*, 1.34 mm (SD = 3.04–0.97 mm) for *Y*, and 1.75 mm (SD = 2.74–0.64 mm) for *Z*. The change in *XYZ* is illustrated for each group in Figure 9.

3.1 | Statistical analysis

A significant difference ($p < 0.0001$) was reported between defect versus SSM and plan versus SSM difference in CoR. A statistical difference ($p < 0.0001$) was also found between defect

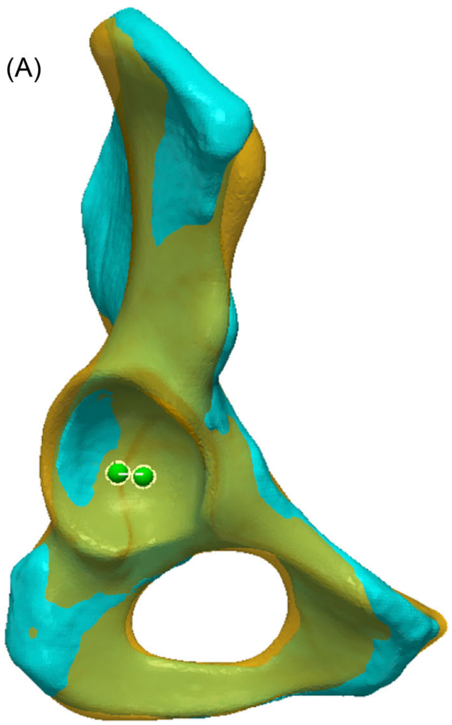

FIGURE 5 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the contralateral healthy side. [Color figure can be viewed at wileyonlinelibrary.com]

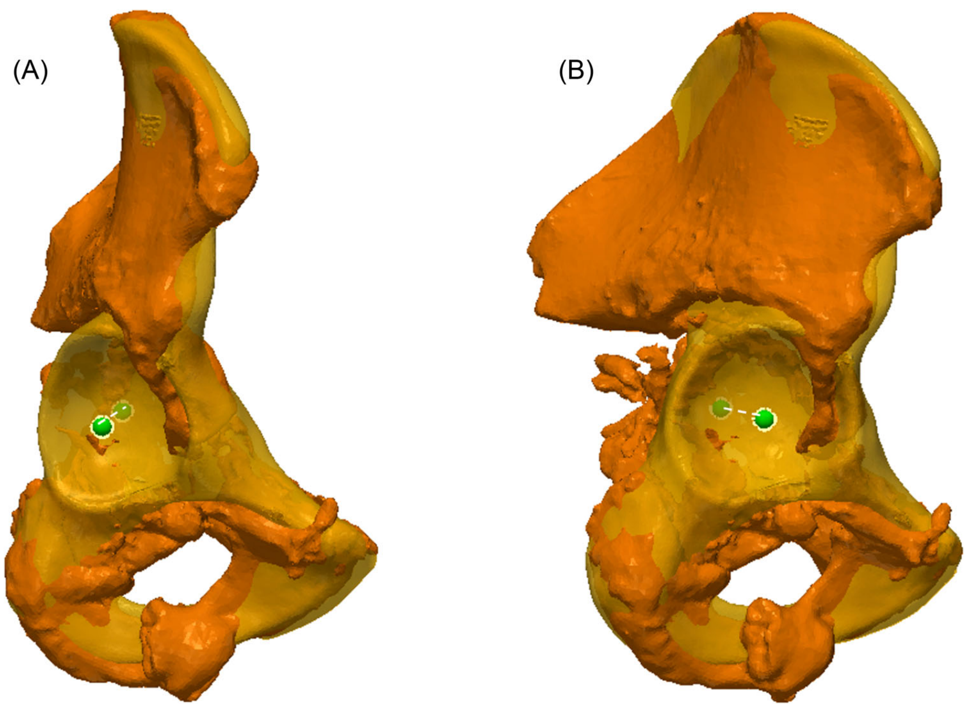

FIGURE 6 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the diseased hip—significant change in *X* is observed. [Color figure can be viewed at wileyonlinelibrary.com]

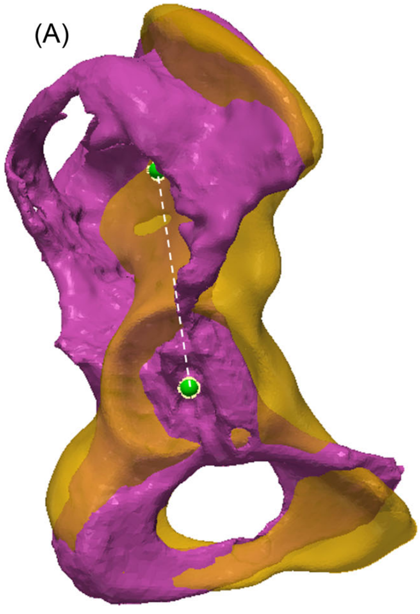

FIGURE 7 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the diseased hip—significant change in *Y* is observed. [Color figure can be viewed at wileyonlinelibrary.com]

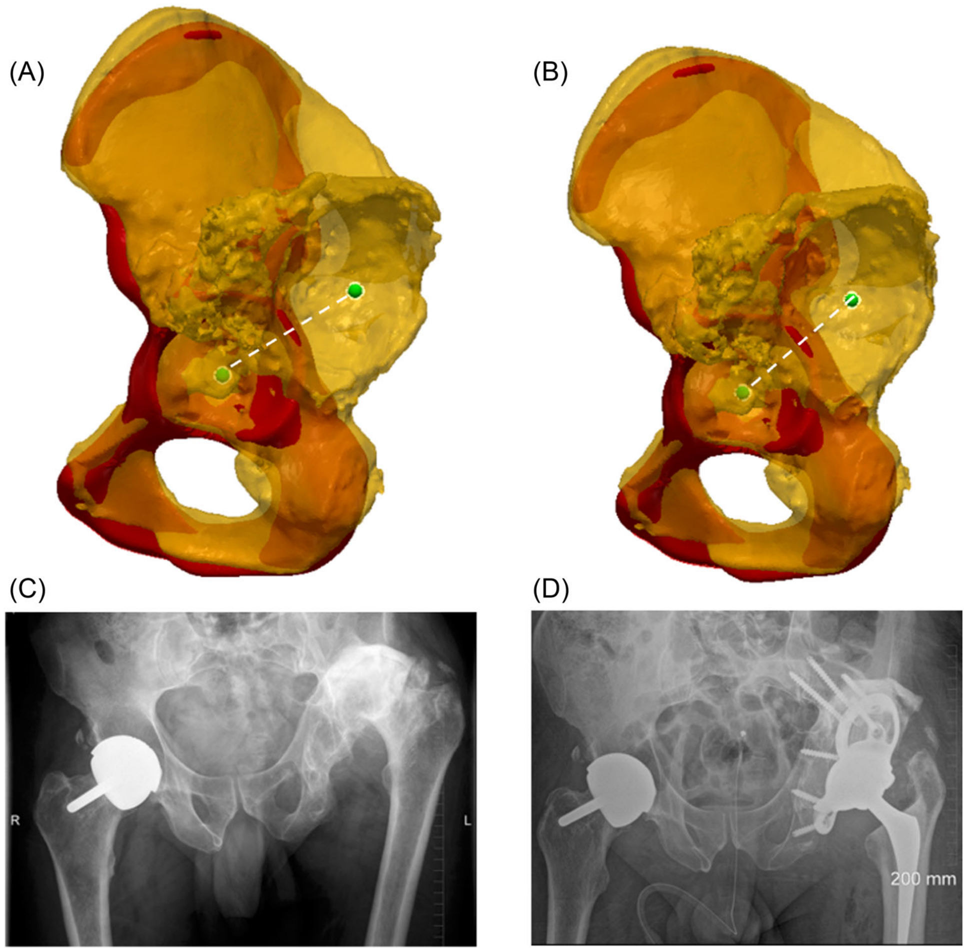

FIGURE 8 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation (CoR) between the Statistical Shape Model and the diseased hip—significant change in *Z* is observed. (C) Anteroposterior plain radiographs taken preoperatively and (D) postoperatively showing restoration of the CoR. [Color figure can be viewed at wileyonlinelibrary.com]

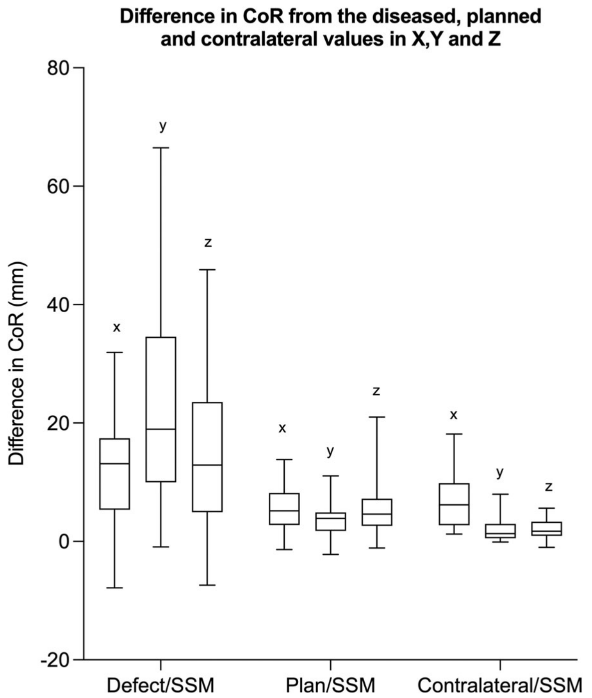

FIGURE 9 Center of rotation (CoR), expressed as differences between the Statistical Shape Model (SSM) and the diseased, planned, and contralateral values in *X*, *Y*, and *Z*.

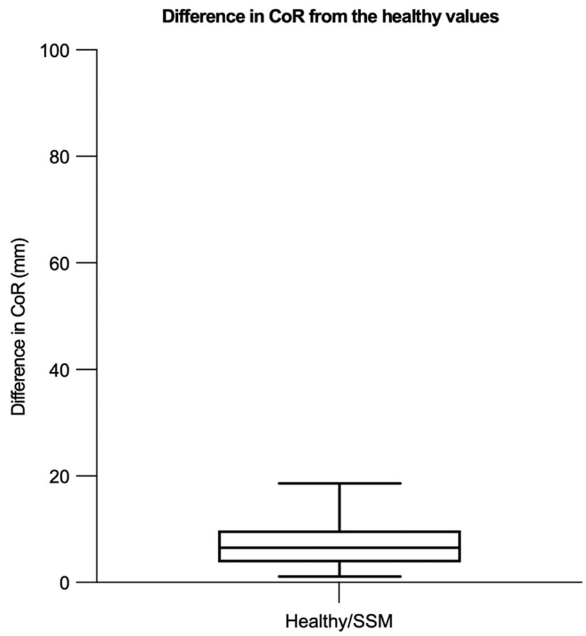

FIGURE 10 Center of rotation (CoR), expressed as differences between the Statistical Shape Model (SSM) and the healthy values.

versus SSM and contralateral versus SSM difference in CoR. No statistical difference ($p > 0.05$) was detected between plan versus SSM and contralateral versus SSM difference in CoR.

3.2 | Validation

The median difference in CoR between the healthy hemipelvises and their SSMs was 5.69 mm (IQR: 6.37–3.77 mm). Figure 10 shows the validation results. An average case is illustrated in Figure 11. The largest displacement in CoR was found in the coronal plane. The median difference in CoR was 2.37 mm (IQR: 4.02–1.70 mm) for *X*, 1.75 mm (IQR: 3.84–0.55 mm) for *Y*, and 3.24 mm (IQR: 4.03–0.96 mm) for *Z*. Figure 12 highlights the change in CoR concerning *XYZ*.

4 | DISCUSSION

The preoperative assessment of large acetabular defects such as Paprosky type III is challenging.[20] Acetabular bony defects have previously been analyzed using 2D radiographs and classified according to a specific scheme. Classification systems can predict the nature of the bone defect and aid the surgical planning of the reconstruction. The most common systems to classify acetabular defects are the Paprosky classification,[1] Gross classification, and the American Academy of Orthopaedic Surgeons (AAOS) classification.[21]

As these represent subjective classification systems, they are affected by the surgeon's experience and have shown highly variable intraobserver and interobserver reliabilities.[22–25] Additionally, being based on the analysis of anteroposterior radiographs of the pelvic bone, they may not provide an accurate representation of the defect size as areas of lysis and other anatomical structures may be obscured. Despite the lack of reliability, these systems are commonly used and no established 3D system for the assessment of bone defects has yet been developed.

Three-dimensional imaging and SSM-based virtual reconstruction techniques can aid the analysis of acetabular bone defects as well as objectively quantify their severity. Vanden Berghe et al.[14] described an SSM-based virtual anatomical reconstruction method of bone defects based on 102 healthy pelvises. The reconstruction process was validated on virtually created defects. The lowest reported CoR had a median of 3.2 mm (IQR: 4.4–2.1 mm). While the study reports acceptable reconstruction errors for clinical applications, no clinical cases were used to evaluate the model and it is unclear how the model would perform on real defects. Hettich et al.[15] proposed an SSM-based method to quantitatively assess acetabular bone defects. The SSM was trained on 66 healthy pelvises and was used to reconstruct the native pelvis of two cases categorized as Paprosky IIIA defects. The reconstruction method was validated on four scenarios of absent bone structures created virtually. The smallest reconstruction CoR error had a median of 3.0 mm (IQR: 7.0–0.5 mm). No difference in CoR between the two real pathological cases and their respective SSM models was reported.

Krol et al.[16] implemented a gender-specific SSM reconstruction method for pelvic bones with oncological defects in eight clinical

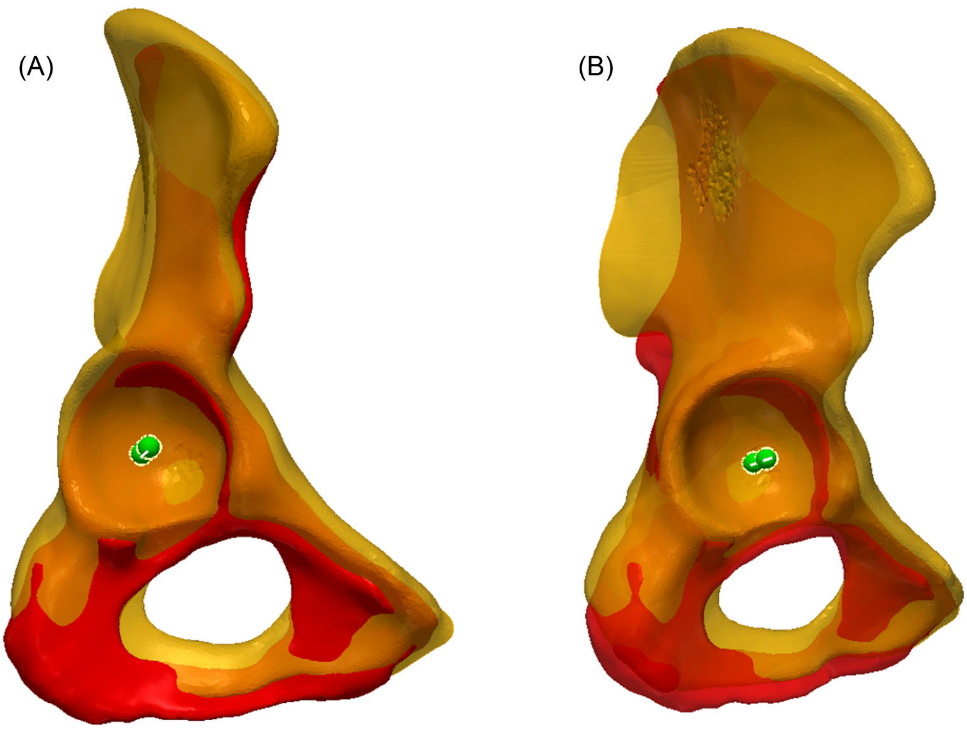

FIGURE 11 (A) Anterior–posterior and (B) lateral views of the difference in center of rotation between the Statistical Shape Model and the healthy side. [Color figure can be viewed at wileyonlinelibrary.com]

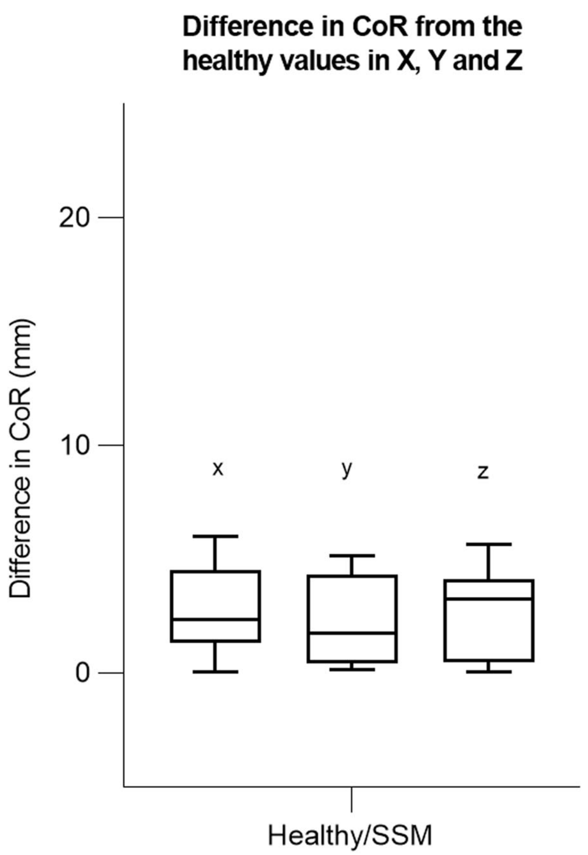

FIGURE 12 Center of rotation (CoR), expressed as differences between the Statistical Shape Model (SSM) and the healthy values in *X*, *Y*, and *Z*.

cases, obtaining the same clinically acceptable accuracy level as the mirroring technique. The SSM was used to retrieve the correct bone shape after tumor resection and guide the cutting of the pathological region during pelvic osteotomy. Fifty male and 50 female pelvises formed the training set for each of the two pelvic SSMs. Eight tumor-damaged pelvic bones were then evaluated using the gender specific pelvis SSMs and a comparison with the traditional mirroring technique was carried out. Although this study has the largest patient cohort, the defect was located within the acetabulum in four out of the eight cases and the change in CoR discrepancy was not investigated.

From our analysis, the CoR of the pathological hips were placed within 31 mm of the SSM reconstructed model on average. The CoR of the plan was located within 9 mm of the SSM model, excluding seven cases where the surgeon chose to keep a high CoR. For those cases, the aim was not to restore the native CoR. The CoR of the healthy contralateral side was located within 8 mm of the SSM. No statistical difference ($p > 0.05$) was found between the plan versus SSM and contralateral versus SSM difference in CoR, for those patients whose surgical plan was to restore the native CoR. From our validation, the mean difference in CoR between the healthy model and the SSM was 5.69 mm (IQR: 6.37–3.77 mm). Direct comparison between our study and the above literature is challenging as our CoR discrepancies were based on patients with Paprosky IIIB defects and not on virtually created ones. Overall, the results are promising and showed that the SSM can be used as a reference to guide the surgical planning of hip revision surgery whenever the contralateral side is diseased or has an implant.

The preoperative and postoperative radiographs further investigate the use of SSM when the contralateral anatomy is diseased or replaced. The patient presented with a right failed hip implant. As an implant was also present on the other side, no contralateral anatomical landmark could be used as a reference to calculate the CoR of the side of interest. Using SSM over standard 3D preoperative planning would have allowed us to derive the anatomical landmarks absent in the failed hip joint and reconstruct the CoR of this complex case (Figure 8).

We acknowledge limitations. First, as the aim of the surgical plan is not always to restore the native CoR, seven patients had to be excluded from the plan versus SSM comparison, and corresponding statistical analysis. Lastly, a larger patient cohort should be used to further assess whether the model is able to cope with different types of severe acetabular defects or deformities. Other factors, such as age, could also be investigated and pelvises of the younger population could be incorporated into the training sets.

5 | CONCLUSION

Planning hip reconstruction in patients with large acetabular defects is difficult due to the lack of anatomical landmarks, as a result of the deformed anatomy and contralateral hip being often replaced. In addition, the presence of the failed implants creates metal artifacts that obscure bony readings from CT scans making the 3D reconstruction challenging. SSM can be used to overcome these limitations. We present the first study that applies an SSM tool to a cohort of 38 patients with Paprosky IIIB defects. Our findings show that SSM can be used to successfully reconstruct the absent bony landmarks of diseased anatomies regardless of the severity of the defects. SSM is an important tool to estimate the original position of the CoR before the development of the bony defect, and it is a valid starting point for engineers to design customized implants for the treatment of patients with large acetabular defects.

AUTHOR CONTRIBUTIONS

Sara De Angelis, Johann Henckel, Anna Di Laura, and Alister Hart contributed to the study design. Sara De Angelis, Johann Henckel, Anna Di Laura, Sean Bergiers, Harry Hothi, and Alister Hart contributed to data acquisition and analysis. Sara De Angelis, Johann Henckel, Anna Di Laura, Sean Bergiers, Harry Hothi, and Alister Hart contributed to the interpretation of data. Sara De Angelis, Johann Henckel, and Anna Di Laura wrote the first draft of the manuscript. Sara De Angelis, Johann Henckel, Anna Di Laura, Harry Hothi, and Alister Hart edited the manuscript. All authors have read and approved the final submitted manuscript.

ACKNOWLEDGMENTS

The authors are grateful to the engineers at Lima Corporate and to the team at Synopsys Simpleware for their technical support. This research was supported by The Arthroplasty for Arthritis Charity, The Maurice Hatter Foundation, The RNOH Charity, The Rosetrees Trust, and The Stoneygate Trust and by researchers at The National Institute for Health Research, University College London Hospitals Biomedical Research Centre.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ORCID

Sara De Angelis http://orcid.org/0000-0002-2721-7694
Harry Hothi http://orcid.org/0000-0001-8745-2111
Alister Hart http://orcid.org/0000-0003-1281-6886

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How to cite this article: De Angelis S, Henckel J, Bergiers S, Hothi H, Di Laura A, Hart A. Statistical shape modeling of the large acetabular defect in hip revision surgery. *J Orthop Res*. 2023;1-10. doi:10.1002/jor.25547