LEVERAGING EXISTING C-ARMS FOR RSA ANALYSIS

Vivian WJ Chung[1,2]*, Robyn Newell PhD[1,2], Angela Kedgley PhD[3], Bassam A. Masri MD[2,4], Shahram Amiri PhD[1,2,4], Antony Hodgson PhD[1,2]

[1]* Dept. of Mech. Engineering, University of British Columbia, Vancouver, V6T1Z4, Canada

[2] Centre for Hip Health and Mobility, Vancouver, V5Z 1M9, Canada

[3] Dept. of Bioengineering, Imperial College London, London, SW7 2AZ, United Kingdom

[4] Dept. of Orthopaedics, University of British Columbia, Vancouver, V6T1Z4, Canada

INTRODUCTION

First introduced over 40 years ago, Roentgen Stereophotogrammetric Analysis (RSA) enabled surgeons to detect relative motions of implants and bones to sub-millimetric precision. These RSA-detected micromotions can be used to monitor implant migration and aid the diagnosis of implant loosening in joint replacement patients.[1–3] While RSA can provide valuable data to clinicians and researchers, most existing RSA systems are expensive.[1,4,5] As a result, RSA is rarely used clinically and is accessible to relatively few researchers around the world.

In contrast, almost all hospitals in developed countries have access to mobile C-arm fluoroscopy machines. In this study, we sought to understand whether we could use a C-arm-based RSA system to make clinically-relevant micromotion measurements, e.g., for use in diagnosis of loosening in Total Knee Arthroplasty (TKA) patients.

MATERIALS AND METHODS

An RSA system requires three main components: dual X-ray units, a calibration device and analytical software. A calibration device with beads of known coordinates is required to obtain the 11-parameter Direct Linear Transform (DLT) for each X-ray source, which provides the necessary information to reconstruct any observable point on images captured simultaneously by the two X-ray units.[6,7]

Radiographic Setup

Our radiographic setup will ultimately consist of two C-arms. During the system development phase, we are employing only a single C-arm (ARCADIS Orbic 3D®, Siemens AG, Erlangen, Germany) that is readily available to us in our laboratory. This is acceptable for phantom work, as the phantoms remain stationary as we reposition the C-arm to acquire the second radiograph. We have also constructed a bi-planar calibration device that can surround the phantom. This enables us to use the same radiographs for both calibration and point reconstruction, thus reducing the need to reposition the single C-arm more than once per exam.

Distortion Correction

To reduce geometric distortion of the radiographs, we used open-source distortion correction software developed by XROMM[8] (X-Ray Reconstruction of Moving Morphology), an ongoing RSA project at Brown University (Providence, RI).

Using the radiograph of a perforated sheet metal, XROMM compares the distances between the perforations against an idealized spacing. A Local Weighted Mean (LWM) approach is then used to derive a corrective transform that is applied to subsequent images captured by the C-arm.[8]

Calibration & 3D Point Reconstruction

The calibration device consisted of 50 stainless steel beads of 2 mm diameter mounted on four polycarbonate sheets (1598K18 and 8707K144, McMaster-Carr, Robinson, NJ). The coordinates of each bead was determined using a Coordinate Measuring Machine (CMM) capable of 0.0001 mm resolution (Crysta-Apex C, Mitutoyo Corporation, Japan).

Similar to distortion correction, the software adopted for calibration and 3D point reconstruction was also developed by XROMM. After point reconstruction, custom software developed in MATLAB (Mathworks, Natick, MA) provided system visualizations (Figure 1) and relative motion calculations using the Singular Value Decomposition[9] method.

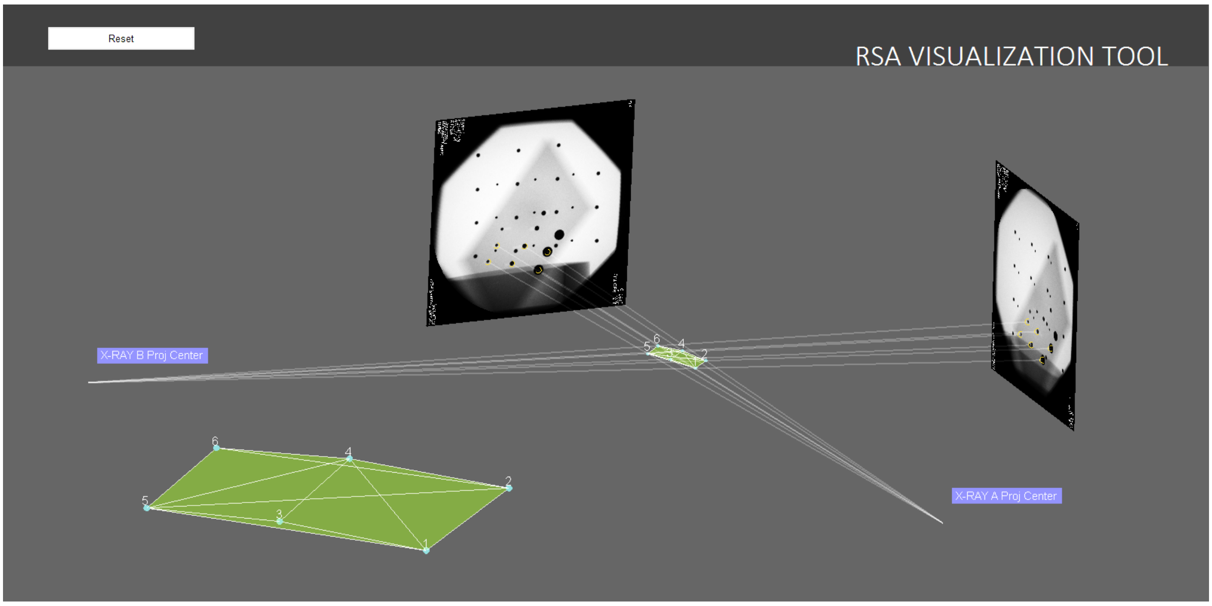

Figure 1: Screenshot of custom-made software showing reconstructed phantom markers within the RSA setup

Preliminary Validation

For initial validation of the system, a phantom of six stainless steel beads attached rigidly to a single polycarbonate panel was constructed. The centroid location of each bead was identified through four RSA examinations. For each examination, the phantom was repositioned in a different orientation.

To evaluate system precision, seven combinations of two rigid bodies were defined, with each rigid body consisting of three beads (Table 1). The centroid-to-centroid distance between rigid bodies was calculated using the four examinations. All rigid body errors between examinations were under 0.19 mm, which is within the guidelines presented by Valstar (2005) for motion calculations.[10]

To assess absolute accuracy, four of the six bead locations were identified using CMM (each bead was contacted by the CMM probe four times from four different directions). Two of the beads were excluded since they were embedded too deeply into the polycarbonate panel for the CMM probe to contact. With an insufficient number of beads to define two rigid bodies, we instead assessed the distances between each possible pair of beads.

RESULTS

In terms of precision, our results yielded standard deviation ranging from 0.021 to 0.049 mm. In the inter-bead accuracy test, the RSA versus CMM measurements showed a mean difference of 0.033 mm. The standard deviation of these differences was 0.075 mm (Table 1).

	Marker Combinations	RSA (based on four exams)		CMM (based on one exam)	Mean Difference (CMM-RSA) [mm]
		Mean Distance [mm]	Standard Deviation [mm]	Distance [mm]	
Precision Test: Distance between rigid body centroids	1,2,4 and 3,5,6	38.5872	0.0210	-	-
	1,2,3 and 4,5,6	31.5823	0.0312	-	-
	1,4,5 and 2,3,6	6.1666	0.0244	-	-
	1,3,4 and 2,5,6	13.5769	0.0469	-	-
	2,3,4 and 1,5,6	21.0127	0.0490	-	-
	1,2,5 and 3,4,6	15.7235	0.0471	-	-
	1,2,6 and 3,4,5	22.0231	0.0431	-	-
Accuracy Test: Distance between marker centroids	1 and 3	26.9943	0.0674	26.9517	-0.0425
	1 and 5	51.4879	0.0175	51.5097	0.0218
	1 and 6	43.5304	0.0688	43.5252	-0.0052
	3 and 5	24.5474	0.0648	24.5946	0.0472
	3 and 6	18.7633	0.0216	18.9136	0.1503
	5 and 6	16.0377	0.0281	16.0653	0.0277

Table 1: Preliminary validation results of our RSA system

DISCUSSION

In this study, we have demonstrated a fully functional RSA system suitable for phantom and cadaveric studies using a single C-arm. Our preliminary precision values are comparable to those reported by Laende (2009): 0.017 to 0.044 mm[11]. Solomon (2010) and Duffy (2006) likewise reported comparable precisions of 0.016 and 0.02 mm for their respective RSA systems.[12,13] Our accuracy results are similar to those of Kärrholm (1997), who also validated an RSA system using CMM as the gold standard.[3] They reported a mean difference of 0.007 to 0.025 mm and a standard deviation of 0.040 to 0.214 mm for translations along three orthogonal axes.

We acknowledge that our validation results were based on distances between two markers, in contrast to Kärrholm's rigid body approach which used at least three markers. In addition, the CMM measurements reported here were not repeated, so there may be additional variability introduced upon re-measurement. Finally, we have not directly validated the accuracy of our system in assessing micromotion, and have yet to add a second C-arm for simultaneous image acquisition. However, the level of accuracy appears to be close to what would be required for our intended application.

In summary, by leveraging open-source software provided by XROMM and an existing C-arm, we have been able to reconstruct 3D locations of radiopaque markers to accuracies comparable to purpose-built systems for a cost of less than $1,500 USD. Although further validations with micro-manipulated phantoms will be required, preliminary findings are promising. Upon successful validation of our marker-based RSA system, we aim to further develop the system into a model-based system[14,15] for use in clinically-driven studies.

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DISCLOSURES

No relevant disclosures.

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