Purpose: Imaging the knee under realistic load-bearing conditions can be carried out in a horizontal plane using a C-arm CT scanner. Human subjects can be scanned in a standing position and acquired data successfully reconstructed. However, reconstructing this data is a challenge due to significant artifacts that are induced due to involuntary motion. Here, we propose motion correction methods in 2D and 3D.

Methods: Four volunteers were scanned for 8 seconds while squatting with ~30 degree flexion. Eight tantalum fiducial markers suitably attached around the knee were used to track motion. The marker position in each projection was semi-automatically detected. Each marker's static 3D position, which served as a reference to correct temporal motion, was estimated by triangulating each marker's 2D position from 248 projections using known projection matrices. Motion was corrected in 3 ways: 1) 2D projection shifting based on the mean position of markers, 2) 2D projection warping using approximate thin-plate splines, 3) 3D rigid body warping.

Results: The original reconstruction was severely motion-corrupted which made it impossible to distinguish the boundaries of bones. Reconstruction with projection shifting and warping in 2D improved visualization of edges of soft tissue as well as bone. A simple numerical metric of residual bead deviation from static position was reduced from 3.2mm to 0.4mm. The 2D-based methods are inherently limited in that they cannot fully accommodate different 3D movements at different depths from the X-ray source. Reconstruction with 3D warping shows clearer edges and less streak artifact than the 2D methods.

Conclusions: The proposed three motion correction methods effectively reduced motion-induced artifacts in the reconstruction and are therefore suitable for weight-bearing scanning. Future work includes scanning patients in standing position after contrast injection for evaluating the soft tissue structure and constructing 3D finite element models for the estimation of joint cartilage stress.

Fiducial marker-based motion compensation for the acquisition of 3D knee geometry under weight-bearing conditions using a C-arm CT scanner

A volunteer was scanned while standing in a C-Arm CT. The C-Arm rotates in a horizontal plane. One-mm Tantalum markers were suitably attached around knee.

Innovation/Impact: Today's diagnostic methods to investigate knee pathology are limited either to a supine or prone position in MR and CT scanners, or have limited ability to image bone tissue (open magnet systems). A suitable system to investigate this would be a flat-panel angiography system because it has high spatial resolution (0.3x0.3 mm pixel size in 2x2 binning) and good bone contrast. Moreover, it is highly flexible in terms of angulation which allows data acquisition under weight-bearing conditions. However, images acquired while scanning a patient in an upright position are particularly vulnerable to motion. The proposed methods reduce the motion artifacts.

Motion correction methods: The static mean 3D position of a marker can be determined by identifying its location in several projections [1]. Eight markers were used as references to correct time-variant motion. The reference estimation in a C-arm CT system with arbitrary trajectories can be done using a projection matrix and identified markers in projections. Three corrections approaches were compared:

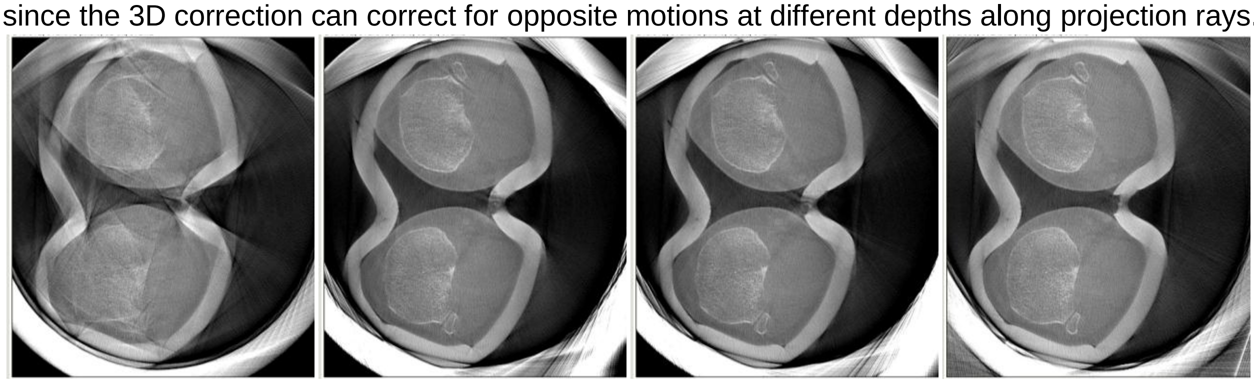
1) Simple projection shifting in 2D: The references in 3D were forward-projected onto a projection. The projection was shifted the amount of the difference (Δu, Δv) between the mean of forward-projected references and the mean of detected markers.

2) Deformable projection warping in 2D using approximate thin plate spline mappings [2]: The detected markers were mapped smoothly onto the forward-projected references. Due to noise of the control point locations, the exact spline interpolation was relaxed.

3) Rigid body warping in 3D: A 3D transformation matrix performs 3 rotations and 3 translations in x, y, and z directions. The 6 parameters for the matrix were optimized to minimize the distance of transformed references from the identified markers in a projection.

Methods	No correction	1) 2D Shifting	2) 2D Warping	3) 3D Warping
Error (pixel/mm)	10.8/3.24	3.7/1.11	1.4/0.42	1.5/0.45

For the purpose of image quality comparison, we used the Euclidean distance between the average locations of the identified markers and the projected references after transformation as error measure. The error measures are comparable for deformable 2D warping and 3D warping (see table). The image quality with 3D warping, however, is better since the 3D correction can correct for opposite motions at different depths along projection rays.



No correction | 1) Projection shifting 2D | 2) Projection warping 2D | 3) Warping 3D

References

[1] T. E. Marchant, A. M. Amer, and C. J. Moore, "Measurement of inter and intra fraction organ motion in radiotherapy using cone beam CT projection images ," Physics in Medicine and Biology, vol. 53, p. 1087, 2008.

[2] G. Donato and S. Belongie, "Approximate thin plate spline mappings," in the 7th European Conference on Computer Vision, 2002, pp. 531-542.