2D/3D Registration for Motion Compensated Reconstruction in Cone-Beam CT of Knees

Subproject C1: Processing and Reconstruction of Medical Image Data
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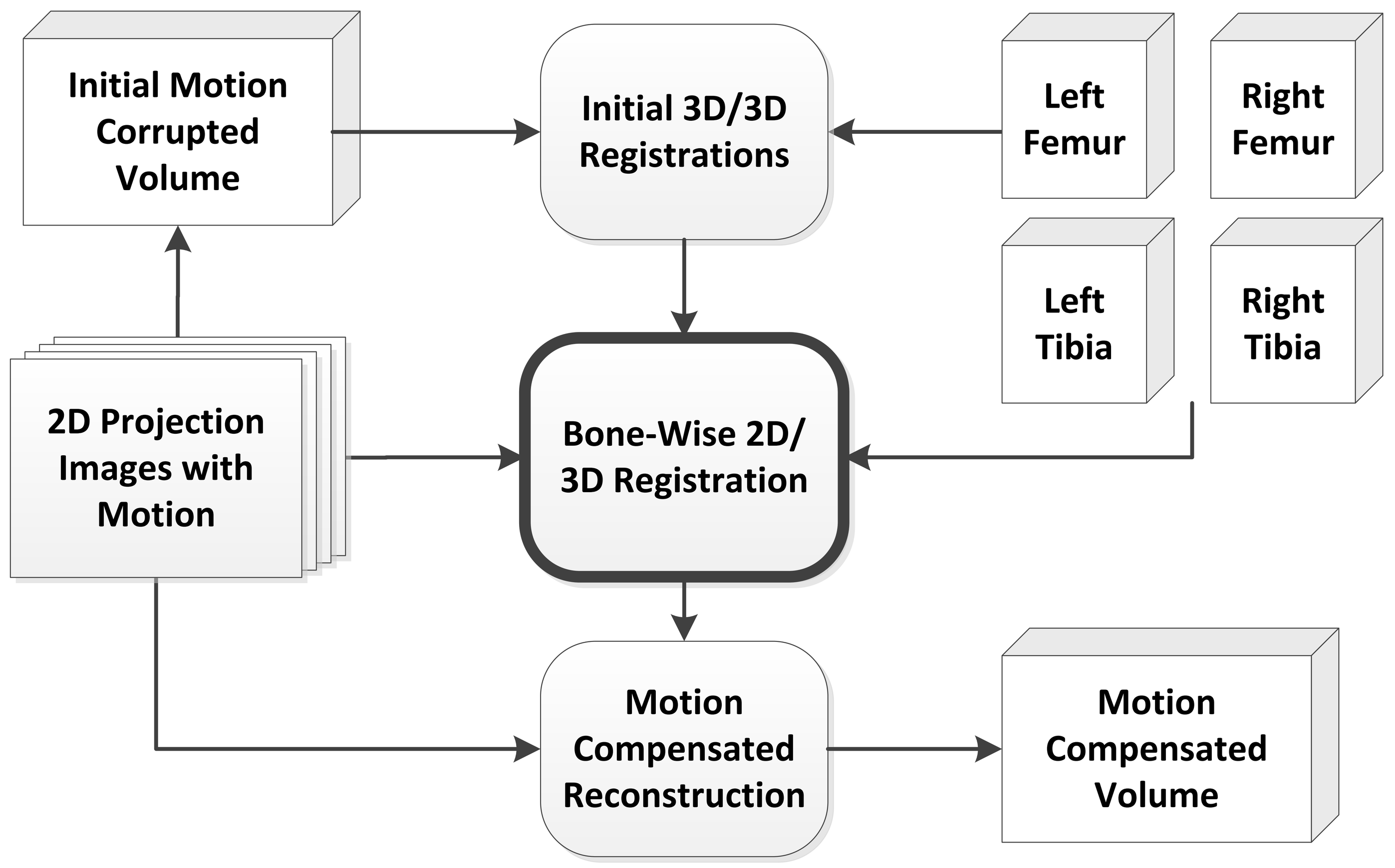
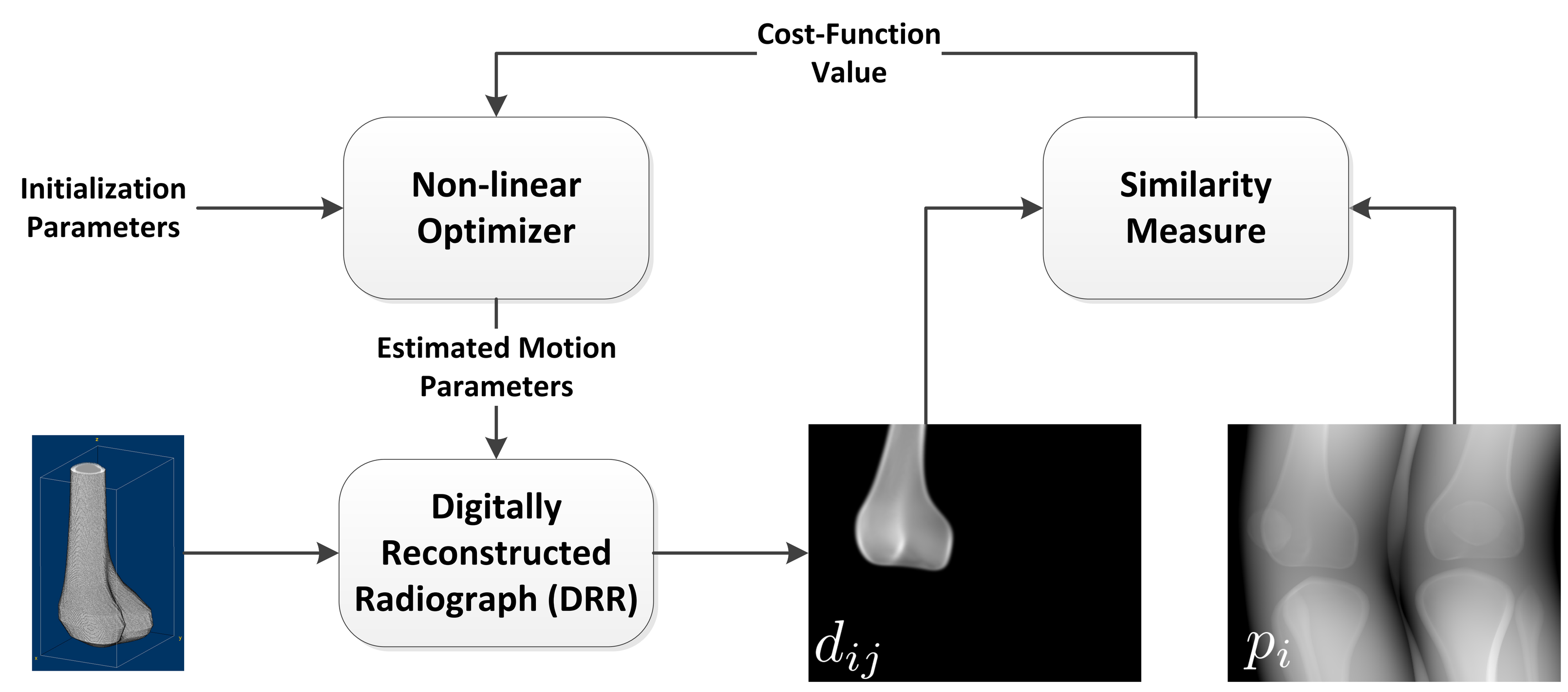
Introduction

- 3D imaging of knee-joint under weight-bearing conditions
- Intra-scan patient motion causes artifacts in CT reconstruction
- Previous work used attached metallic beads to track the motion in projection images [1]
- Marker placement may be bothersome and motion on skin might not reflect internal motion
- Idea: Use 2D/3D registration of motion-free bone volumes to all projection images for motion estimation

Materials and Methods



Bone-Wise 2D/3D Registration



- Similarity measure is crucial in 2D/3D registration
- Gradient Correlation is known to be robust [2]

$$NCC(I_a, I_b) = \frac{\sum_{(u,v)}(I_a(u,v) - \overline{I_a})(I_b(u,v) - \overline{I_b})}{\sigma_{I_a}\sigma_{I_b}}$$

$$\Phi(\mathbf{m}_{1j}, \cdots, \mathbf{m}_{Nj}) = \frac{1}{2}\sum_{i=1}^{N} NCC\left(\frac{\partial d_{ij}}{\partial u}, \frac{\partial p_i}{\partial u}\right) + NCC\left(\frac{\partial d_{ij}}{\partial v}, \frac{\partial p_i}{\partial v}\right)$$

- Require smooth motion over time by regularization

$$\widehat{\Phi}(\mathbf{m}_{1j}, \cdots, \mathbf{m}_{Nj}) = \Phi(\mathbf{m}_{1j}, \cdots, \mathbf{m}_{Nj}) + \lambda \sum_{i=1}^{N} \|\mathbf{m}_{ij} - (\mathbf{m} * \mathbf{g}^{\sigma})_{ij}\|_2^2$$

Experiments

Simulations using the XCAT phantom [3]

- Real motion from camera tracking system incorporated into XCAT model
- Segmentations directly generated from XCAT
- Manual initial 3D/3D registration using SLICER
- Optimization limited to translations: 4 x 3 x 248 = 2976 parameters

Quantitative Results

- Relative root-mean-square-error (rRMSE) and Structural Similarity (SSIM) [4]
- Measures evaluated on ROI around each bone, including soft tissue
- Each ROI was registered to reference
- Final results are mean values over all bones

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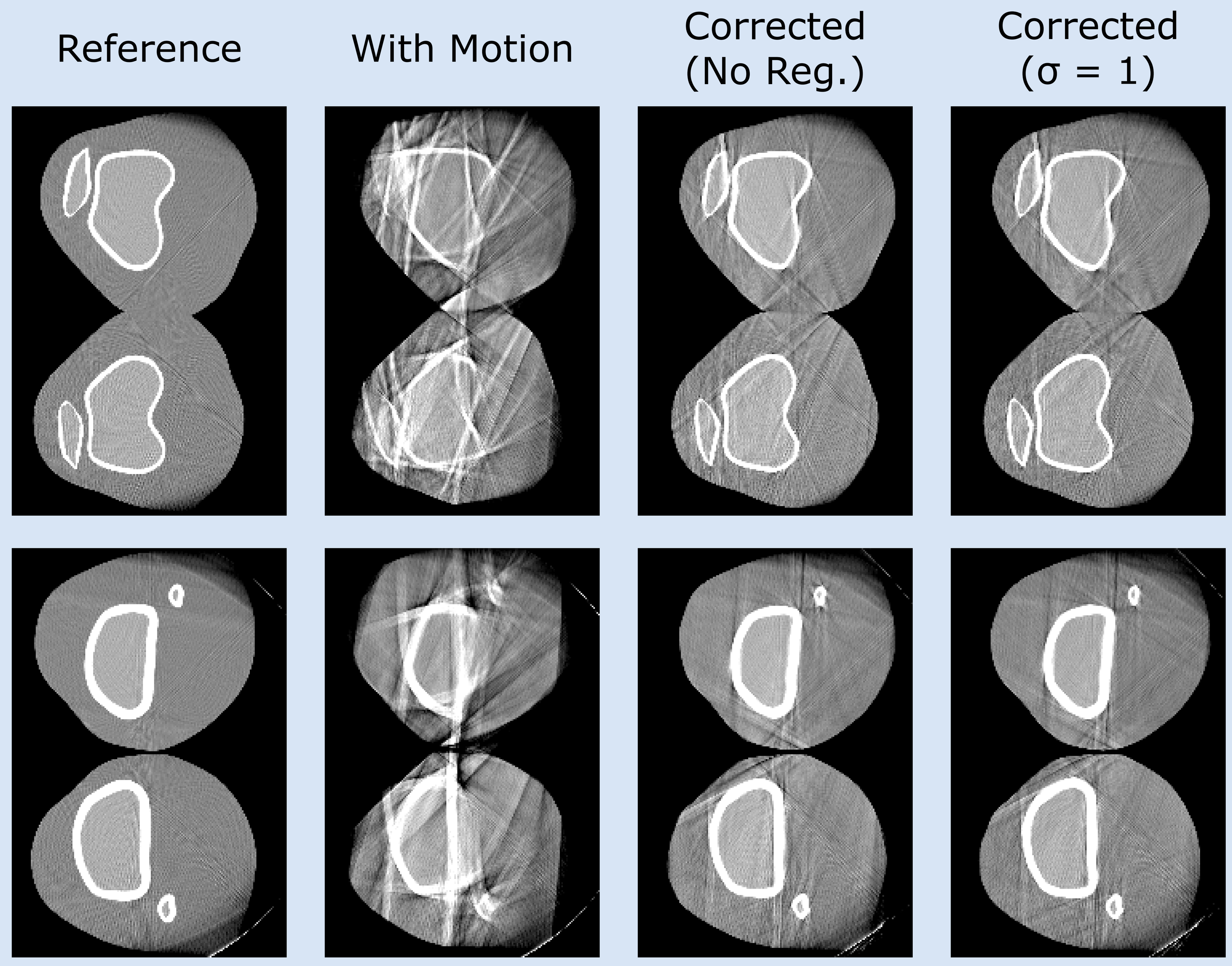

Figure 1: Image reconstructions without motion, with motion and motion corrected with and without regularization

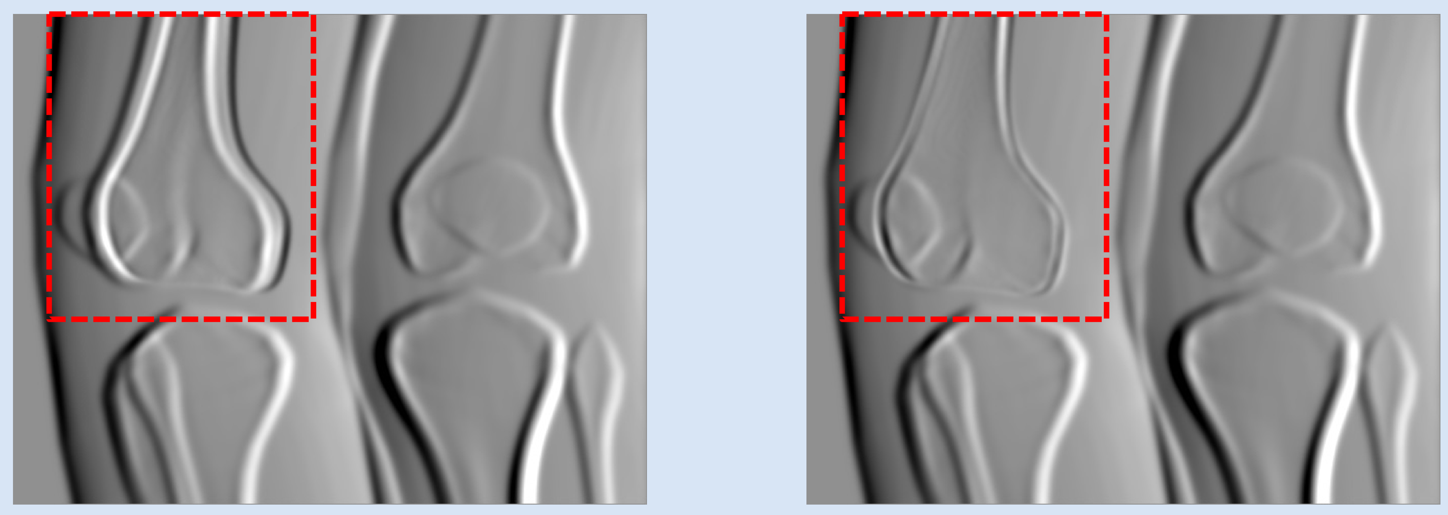

Figure 2: Difference image of horizontal gradient of DRR and acquired projection before and after registration

Results and Discussion

- Bone outline is accurately restored (Fig.1)
- Further artifact reduction with regularization (Fig.1)
- Bone contours well aligned in projection images (Fig.2)
- rRMSE and SSIM support our qualitative results

	With Motion	Corr. (No Reg.)	Corr. (σ=1)	Corr. (σ=2)
rRMSE [%]	12.80	5.78	**5.02**	5.18
SSIM (10^{-2})	38.37	86.02	**88.69**	87.95

Conclusion

- Novel motion estimation using 2D/3D registration
- Substantial increase of image quality compared to a reconstruction without correction
- Regularization can improve results but needs to be applied carefully
- Prior motion-free scan required but usually part of scanning protocol

References

[1] Choi et al. (2014). Fiducial marker-based correction for involuntary motion in weight-bearing C-arm CT scanning of knees. II. Experiment. Medical Physics, 41(6)

[2] Penney et al. (1998). A comparison of similarity measures for use in 2-D-3-D Medical Image Registration. Transactions on Medical Imaging, 17(4)

[3] Choi et al. (2013). Fiducial marker-based correction for involuntary motion in weight-bearing C-arm CT scanning of knees. Part I. Numerical model-based optimization. Medical Physics, 40(9)

[4] Wang et al. (2004). Image Quality Assessment: From Error Visibility to Structural Similarity. IEEE Transactions on Image Processing, 13(4)