Joint Calibration and Motion Estimation in Weight-Bearing Cone-Beam CT of the Knee Joint using Fiducial Markers

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Introduction

Motivation

- Imaging of the knee joint under weight-bearing conditions [1]
- Motion artifacts introduced due to patient motion.

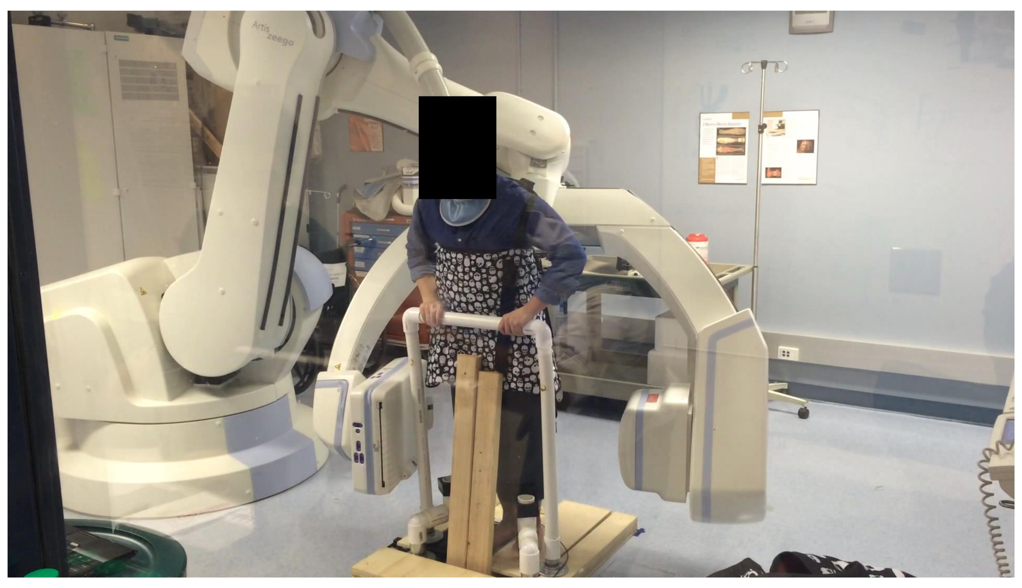

Figure 1: Weight-bearing imaging of knees using a clinical C-arm CBCT [1].

Reference method:

- Motion compensation using fiducial markers [2].
- **Drawback**: requires full calibration before each scan due to horizontal trajectory [3].

Goal:

- Both calibration and motion compensation using fiducial markers.
- Avoid cumbersome calibration step.

Materials and Methods

➢ **Minimizing the reprojection error (RPE):**

$$\underset{\vec{\alpha},\vec{\beta}}{\arg\min}\ f(\vec{\alpha},\vec{\beta}) = \underset{\vec{\alpha},\vec{\beta}}{\arg\min}\ \frac{1}{2}\sum_{j=1}^{J}\sum_{i=1}^{M}||h(\vec{n}) - \vec{u}_{ij}||_2^2$$

with

$$\vec{n} = \mathbf{P}_j(\vec{\alpha},\vec{\beta}) \cdot (\vec{v}_i \quad 1)^\top$$
$$= \mathbf{K}_j(\vec{\beta}) \cdot [\mathbf{R}_j\,|\vec{t}_j\,] \cdot \mathbf{M}_j(\vec{\alpha}) \cdot (\vec{v}_i \quad 1)^\top$$

- Estimated 3D marker position $\vec{v}_i$ and the corresponding 2D position $\vec{u}_{ij}$.
- Motion matrix $\mathbf{M}_j(\vec{\alpha})$ for each projection depending on extrinsic parameters $\vec{\alpha}$.
- Intrinsic camera matrix $\mathbf{K}_j(\vec{\beta})$ for each projection depending on intrinsic parameters $\vec{\beta}$.
- $[\mathbf{R}_j\,|\vec{t}_j\,]$ extrinsic parameters for ideal horizontal trajectory initialization.
- $h(\vec{n})$ divides through the homogeneous coordinate.

Properties:

- ➢ Trajectory initialization using prior knowledge from the datasheet.
- ➢ 6D rigid motion model
  - Modeling patient and system motion .
- ➢ 3D intrinsic camera model suitable for source-to-detector geometry [4]
  - Modeling changing source-to-detector distance (focal length).
  - Modeling tilted detector, which results in shifted central point.

Comparing with:

- Motion compensation using a closed-form solution.
- Reference and an extended version of the reference method (see Fig. 2.B).

Evaluation on:

- Three clinical data.
- One simulated numerical phantom (see Fig. 2.D).

Results

- ➢ **Qualitative evaluation**: Best reconstruction results achieved by the extended reference and the proposed method, cf. Fig. 3 D, E and N, O .
- ➢ **Quantitative evaluation**: Best results achieved by the extended reference and the proposed method, cf. Tab. 1 and Tab. 2 .

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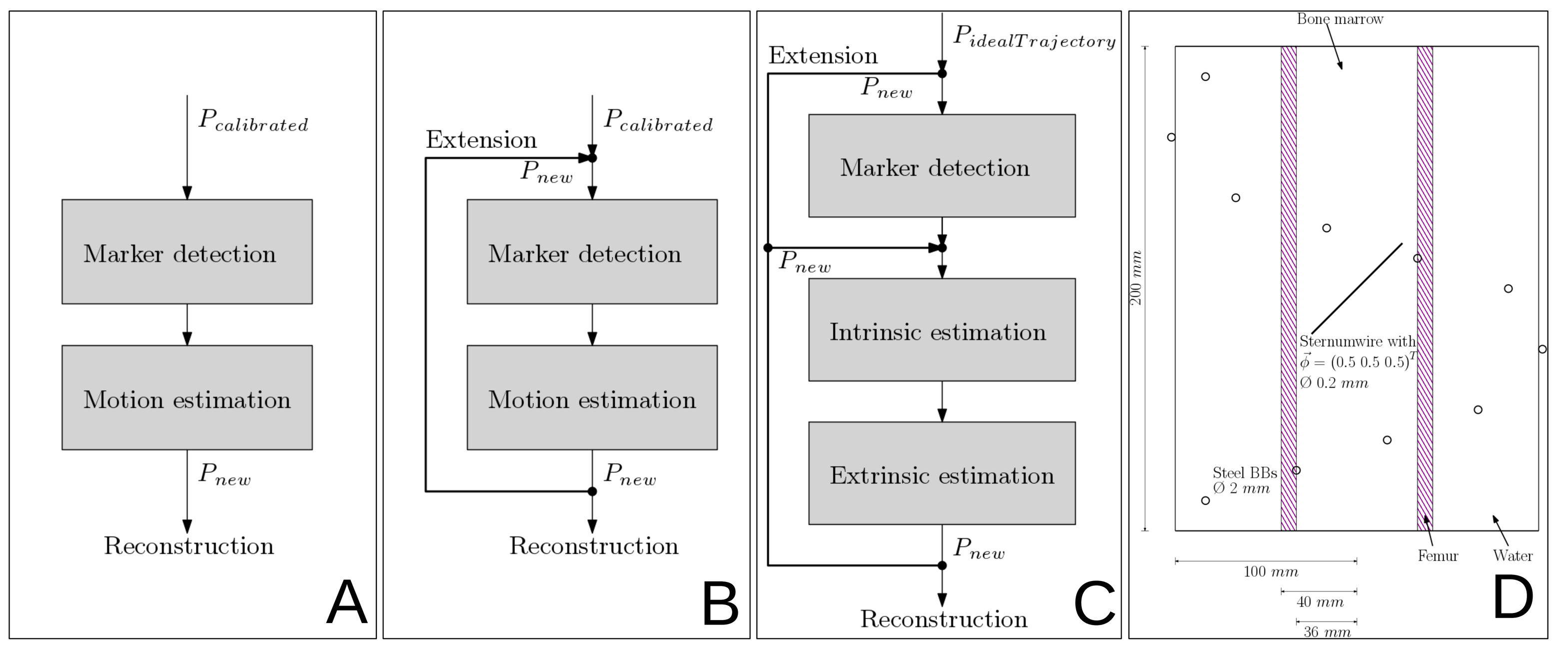

Figure 2: Estimation methods. Phantom.

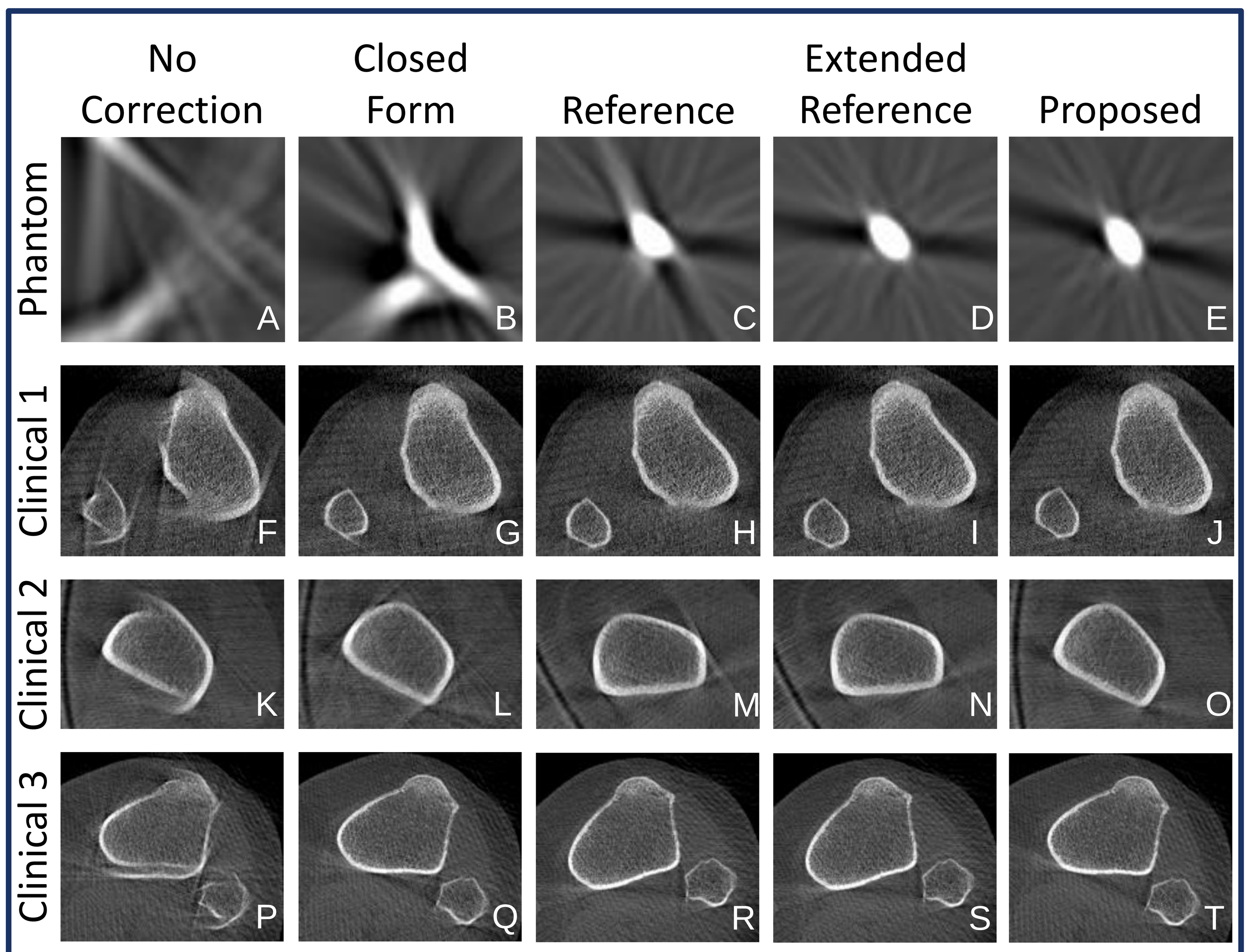

Figure 3: ROI of reconstruction for the different methods.

	Phantom	Clinical 1	Clinical 2	Clinical 3
No Correction	84.85	96.70	71.29	38.20
Closed Form	0.135	9.174	0.396	0.591
Reference	1.367	4.597	0.726	0.617
Ext. Reference	0.088	2.099	0.143	0.561
Proposed	0.088	3.283	0.324	0.535

Table 1: RPE in pixel for the different methods.

	Phantom	Clinical 1	Clinical 2	Clinical 3
Closed Form	0.40±444	0.64±3.5	0.82±1.6	0.80±1.7
Reference	0.36±1.7	0.63±2.7	0.84±3.7	0.81±3.3
Ext. Reference	0.35±2.6	0.63±2.7	0.82±1.3	0.82±2.4
Proposed	0.35±2.6	0.62±2.9	0.81±2.6	0.81±1.7

Table 2: FWHM (median ± std) for the different methods.

Discussion and Conclusion

- We extend the current method with a self-calibration component.
- The results are at least as good as from the reference method.
- ➢ **No calibration necessary while reconstruction quality is preserved.**

Limitations

- Markers have to be attached to the knee.
- Only rigid motion modeled.

References

[1] J.-H. Choi et al., "Fiducial marker-based correction for involuntary motion in weight-bearing c-arm ct scanning of knees. part ii. Experiment," Medical Physics 41(6):091905, 2014.
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[4] W. Wein et al., "Self-calibration of geometric and radiometric parameters for cone-beam computed tomography," Proc. Fully3D Vol. 2, 2011.