Validation of MR-CT deformable registration accuracy and MRI fat-fraction quantification using a novel 3D-printed anthropomorphic phantom

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ABSTRACT

Purpose: To evaluate a MR-CT deformable registration workflow using a novel 3D-printed anthropomorphic phantom that enables controlled, known lumbar spine deformation, with assessment of geometric accuracy and quantitative integrity of MR fat-fraction (FF).

Methods: A phantom was created to allow controlled deformation of the lumbar spine with known directions and magnitudes. Eight MRI datasets (MR0–MR7), acquired under different deformation configurations, were deformably registered to a baseline CT (CT0) using a convert local alignment (CLA) and contour-based (CB) algorithm. Geometric registration accuracy was assessed on contoured structures (L1–L5 vertebrae, sacrum, hips, and total bone) using Dice similarity coefficient (DSC), mean distance to agreement (MDA), Hausdorff distance (HD), and volume differences. The algorithms were compared using paired, two-sided Wilcoxon signed-rank test. Quantitative integrity was evaluated by comparing mean MR %FF values in inserts with known %FF before and after deformation.

Results: Mean DSCs for vertebral and sacral contours were 0.90 (CLA) and 0.93 (CB) with the CB method significantly ($p<0.05$) improving DSC and with corresponding MDA values ≤1mm. HD demonstrated greater variability, particularly for larger structures, with vertebral HD values < 10 mm and hip HD values exceeding 15 mm ($p<0.05$). Hip structures exhibited lower DSCs than spinal structures (mean DSC = 0.72-0.75 (CLA) and = 0.88-0.92 (CB); $p<0.05$). CB deformation preserved total bone volume more consistently than CLA. No correlation was observed between DSC and deformation magnitude. For quantitative evaluation, the mean difference in %FF before and after deformation was -0.60%FF with narrow limits of agreement indicating minimal perturbation of FF.

Conclusion: Using a deformable, anthropomorphic phantom with known lumbar spine displacement, this study demonstrates that the evaluated MR-CT deformable registration workflow maintains stable geometric accuracy for spinal anatomy and preserves quantitative MR FF measurements across the investigated deformation magnitudes, supporting its robustness under controlled deformation conditions.

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INTRODUCTION

Deformable image registration (DIR) is a critical component of modern radiotherapy, enabling alignment of multimodality images, contour propagation, dose accumulation, and adaptive treatment workflows. Despite clinical use, validation of DIR remains challenging. A major limitation is the absence of ground truth in patient data, where the exact deformation is unknown and cannot be directly measured.[1]

Current limitations include:

- Digital phantoms lack anatomical realism and are restricted in available deformation scenarios[2]
- Physical phantoms traditionally lack controllable, realistic deformation
- Quantitative metrics and QA practices vary widely, with no standardized framework for determining acceptable DIR accuracy[3]

As a result, there is a critical need for validation tools that provide known, controllable deformation with realistic anatomy, enabling assessment of both geometric and quantitative accuracy.

Purpose: To evaluate the geometric accuracy and quantitative integrity of an MR-CT DIR workflow using a novel 3D-printed anthropomorphic phantom with known, controlled lumbar spine deformation.

METHODS AND MATERIALS

Phantom Design:

- Anthropomorphic, 3D-printed phantom
- Includes
  - Vertebral bodies (L1-L5), sacrum, hips
  - Fat-fraction (FF) inserts for quantitative assessment
  - Multi-modality compatibility (CT, MR, NM)

Image Acquisition:

- Baseline CT (CT0)
- 8 MR datasets (MR0-MR7) with increasing degrees of deformation

Registration Methods

- MR datasets deformably registered to CT using:
  - Convert Local Alignment (CLA) – focuses the registration within a selected region of interest
  - Contour-Based (CB) – uses delineated anatomical structures to guide registration

Evaluation Metrics:

- Geometric accuracy: DSC, MDA, HD, volume difference
- Quantitative accuracy: mean %FF before vs after deformation

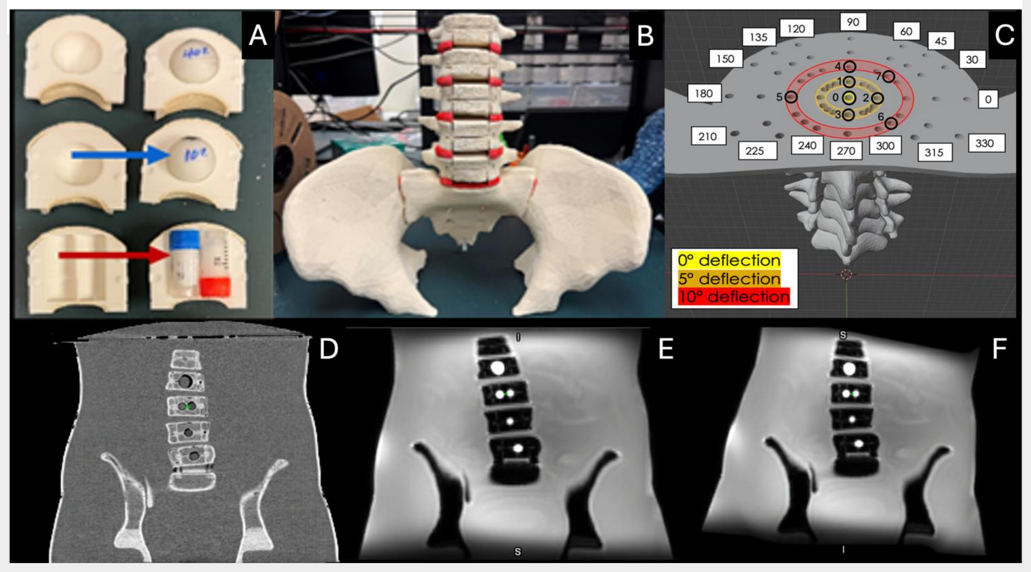

Figure 1. (A) Vertebral bodies that include spherical and vial-based FF inserts. (B) Pelvis and vertebrae region. (C) Available deformed positions with black circles indicating deformed positions (0-7) used. Orange circle has a radius of 7.4 mm and red circle has radius of 14.9 mm from position 0. (D) CT0. (E) MRI acquired with 10° deflection towards patient right. (F) resulting deformed MR image in CT space.

RESULTS

Geometric Accuracy:

- Spine structures (L1-L5, sacrum)
  - DSC ≈ 0.90 (CLA) vs. 0.93 (CB)
  - Jaccard ≈ 0.83 (CLA) vs. 0.87 (CB)
- Hip structures
  - DSC ≈ 0.72-0.75 (CLA) vs. 0.88-0.92 (CB)
  - Jaccard ≈ 0.76 (CLA) vs. 0.86 (CB)
- CB outperformed CLA ($p < 0.05$)

Distance Metrics:

- Spine structures (L1-L5, sacrum)
  - MDA ≤ 1 mm for CLA and CB
  - HD ≈ 5.5 mm (CLA) vs. 4.6 mm (CB)
- Hip structures
  - MDA ≈ 1.42 (CLA) vs. 0.82 (CB)
  - HD ≈ 11.5 mm (CLA) vs. 14.6 mm (CB)
- CB preserved bone volume more consistently

Deformation Sensitivity:

- No correlation between deformation magnitude and DSC

Quantitative Validation:

- Mean %FF difference after deformation: -0.60%
- Narrow limits of agreement: -1.31% to +0.11%

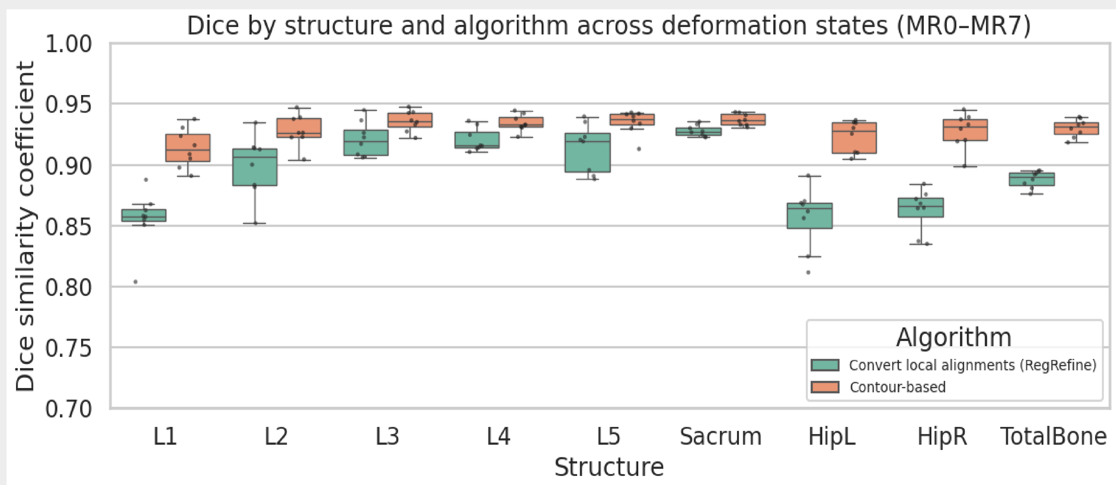

Figure 2. Dice similarity coefficients (DSC) for each contour across eight deformation states following MR-CT deformable image registration (DIR) using convert local alignments (CLA) and contour-based (CB) algorithms. Vertebral structures (L1-L5) and the sacrum demonstrate high overlap with limited variability, while hip structures exhibit lower DSC. CB registration demonstrates higher DSC compared to CLA.

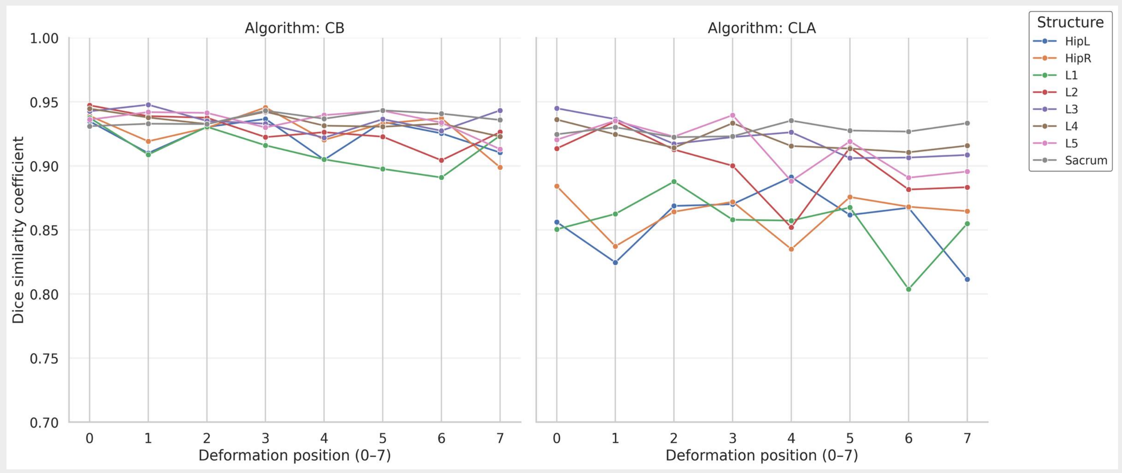

Figure 3. Dice similarity coefficients (DSC) for vertebral (L1-L5) and sacral structures plotted as a function of deformation state (MR0-MR7), corresponding to increasing, known lumbar spine deformation following MR-CT DIR using a contour-based (CB) and convert local alignments (CLA) algorithms. The DSC values remain stable across deformation states, with consistently higher overlap and reduced variability observed for the CB algorithm versus the CLA.

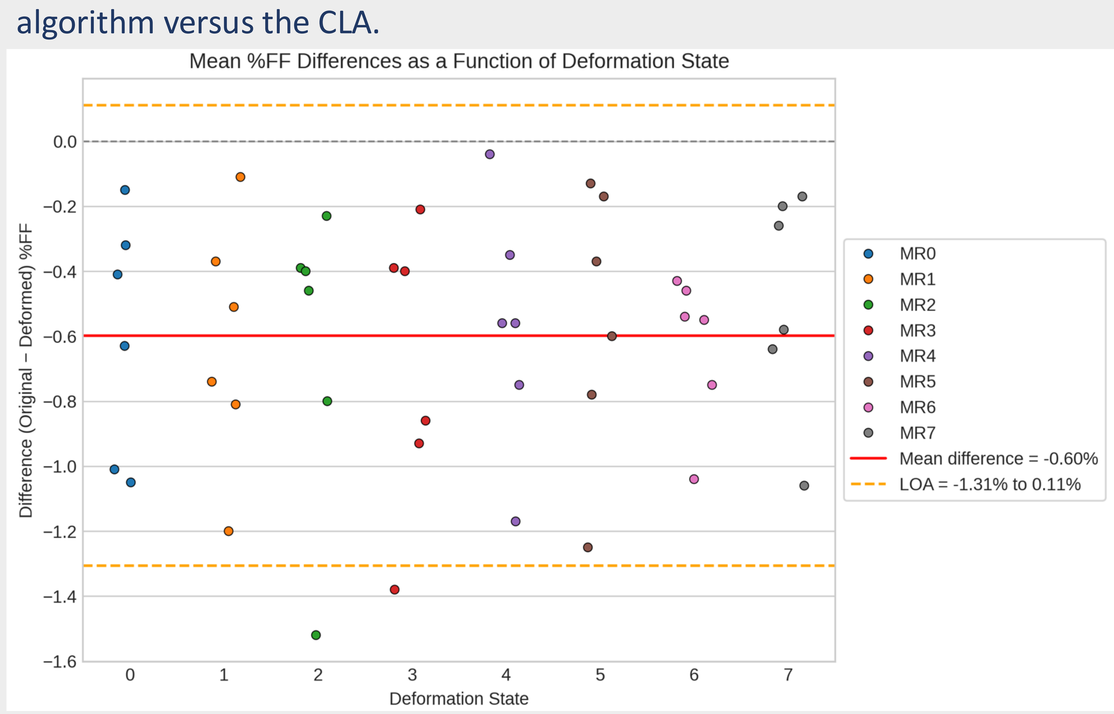

Figure 4. Differences in MR-derived %FF were computed for all ROIs as a function of deformation state. The mean difference (−0.60%FF; solid red line) and 95% limits of agreement (−1.31 to +0.11%FF; dashed orange line) demonstrate close agreement between measurements.

DISCUSSION

This work addresses a major limitation in DIR: the lack of ground truth in patient data. Using a deformable anthropomorphic phantom with known lumbar spine displacement enables direct, controlled validation of DIR performance.

Geometric Accuracy:

- High accuracy observed in spine
- Reduced performance in hips
- CB DIR outperformed CLA, with improved overlap and volume preservation

Quantitative Integrity

- Demonstrates preservation of quantitative information with minimal impact on MR %FF values
- Supports the use of DIR in quantitative imaging workflows

Robustness to Realistic Deformations:

- No observed correlation between deformation magnitude and DSC
- Indicates stable DIR performance across tested conditions
- Still limited to controlled deformation range vs. full patient variability

Limitations:

- Limited to lumbar spine deformation
- Does not fully capture complex multi-organ motion

Future Work:

- Incorporate SPECT imaging into the DIR workflow for further multi-modality DIR validation
- Expand to larger deformation ranges and additional anatomies

CONCLUSIONS

This study demonstrates the feasibility of using a deformable, anthropomorphic 3D-printed phantom to enable ground-truth validation of MR-CT DIR. By introducing controlled and known lumbar spine deformation, this platform supports reproducible evaluation of DIR performance.

Key Findings:

- High geometric accuracy achieved in spinal anatomy
- Stable performance across deformation states
- MR %FF preserved

Significance:

- Addresses a major challenge in DIR validation by providing known anatomical ground truth
- Enables evaluation of both registration accuracy and quantitative integrity
- Provides a reproducible platform for benchmarking DIR algorithms and supporting clinical adoption

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