Weakly-supervised Biomechanically-constrained CT/MRI Registration of the Spine

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Motivation and Contribution

Clinical motivations:
- spinal CT has higher contrast in bony structures
- spinal MRI can detect lesions and tumors of the spinal cord, the intervertebral discs and the inner anatomy of the vertebral bodies

Problems in registering articulated rigid structures:
- rigid registration cannot address the varying curvature of patients' spine during different imaging sessions
- global deformable registration ignores difference between soft tissues and bony structures

Our contributions:

a) Proposal of a framework for **rigidity-preserving** MRI/CT deformable registration of the spine
b) Introduction of the **rigid dice (RD)** loss and **rigid field (RF)** loss for rigidity-preservation
c) Adaptation of rigidity penalties used in conventional registration (**orthonormal condition (OC), properness condition (PC)**) to deep learning image registration
d) Extensive evaluation and ablation study of different losses on an in-house dataset with 167 patients

Proposed Method

Framework workflow:
- Inputs: a CT (moving image) and its label map, an MRI (fixed image)
- Output: a dense displacement field ϕ

Training losses:

a) intensity-based image similarity loss $\mathcal{L}_{sim}$
b) smoothness regularizer on the output DDF $\mathcal{L}_{smooth}$
c) rigidity penalties $\mathcal{L}_{rigid}$ between the moving label and the warped label, or on the deformation vectors inside the rigid bodies

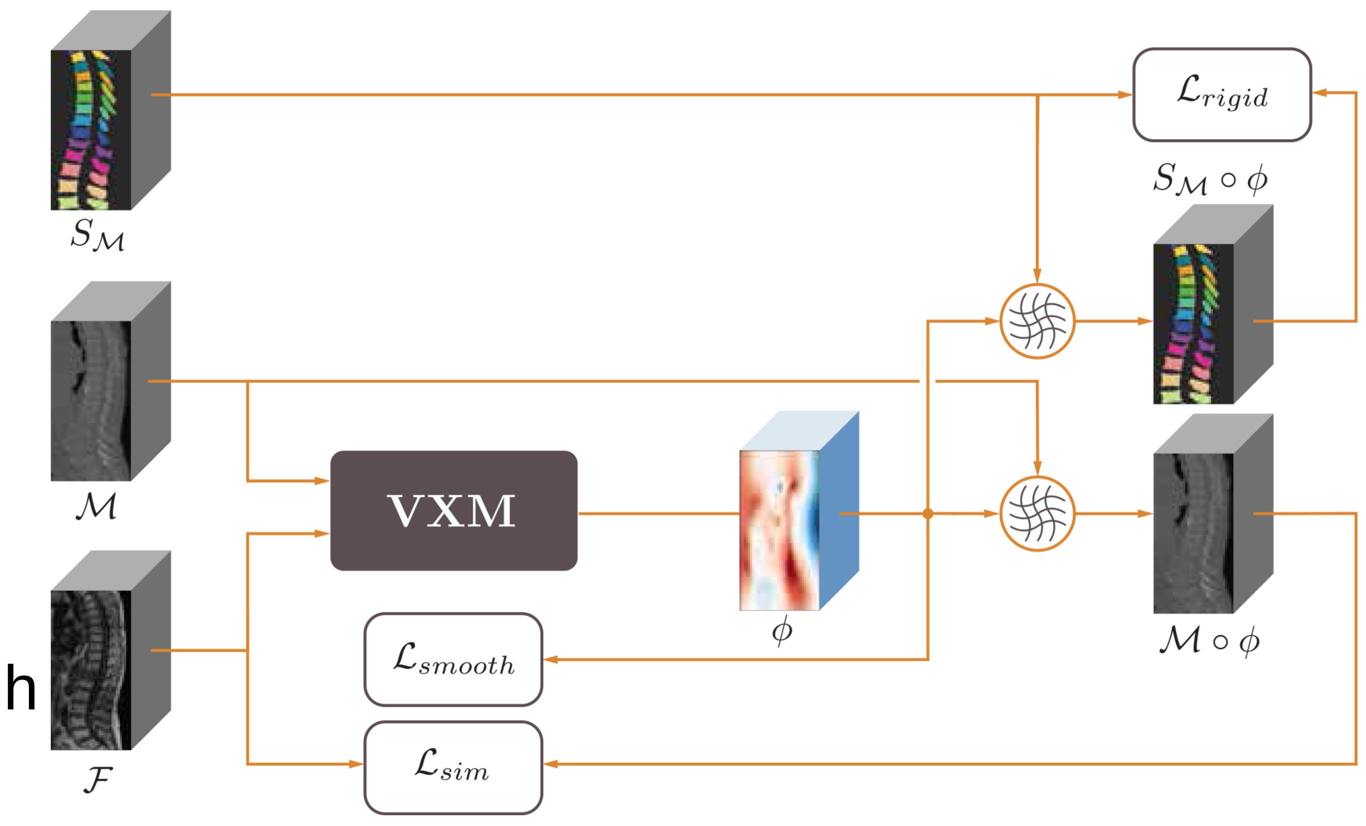


Fig 1. An overview of the architecture.

Rigidity penalties:

Rigid dice loss:
- ✓ Step 1: Compute the closest rigidly transformed label of each vertebra through rigid registration between moving label and warped label
- ✓ Step 2: Calculate the dice loss between the closest rigidly transformed label and warped label

Rigid field loss:
- ✓ Step 1: Sample a set of random points from the moving label of each vertebra
- ✓ Step 2: Compute the corresponding points in the warped label through DDF ϕ
- ✓ Step 3: Compute the average rigid motion for the set of pairing points with SVD (Procruste problem)
- ✓ Step 4: Calculate the MSE loss between the DDF vectors and the average rigid motion vectors inside each vertebra

PC & OC:
- ✓ Step 1: Compute the Jacobian of the DDF inside each vertebra
- ✓ Step 2:
  Properness condition: Calculate the $l2$-distance between the Jacobian determinant and constant one
  Orthonormal condition: Calculate the Frobenius distance between the inner product of the Jacobian and identity matrix

Results

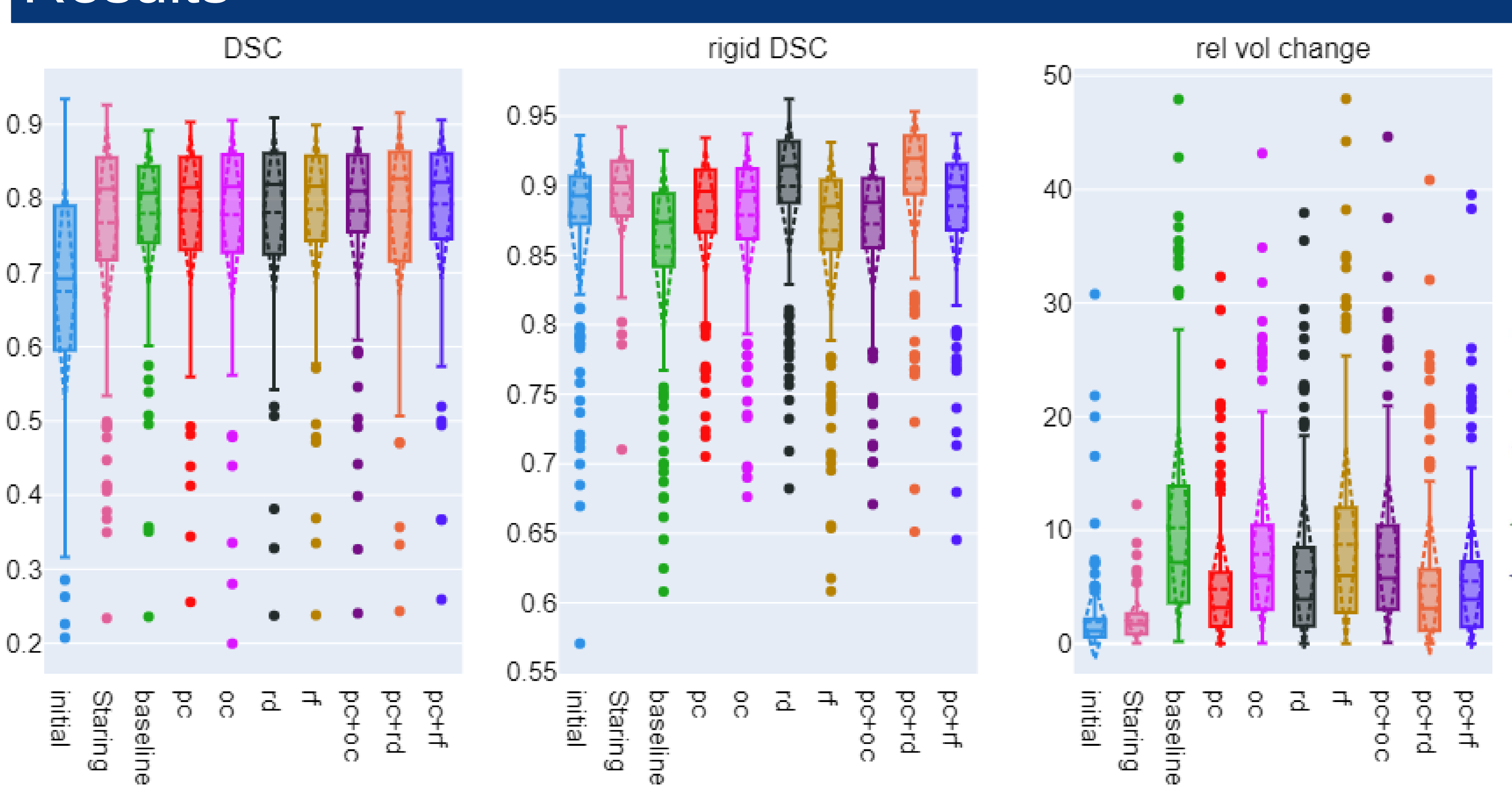


Fig 2. Boxplots of different loss settings

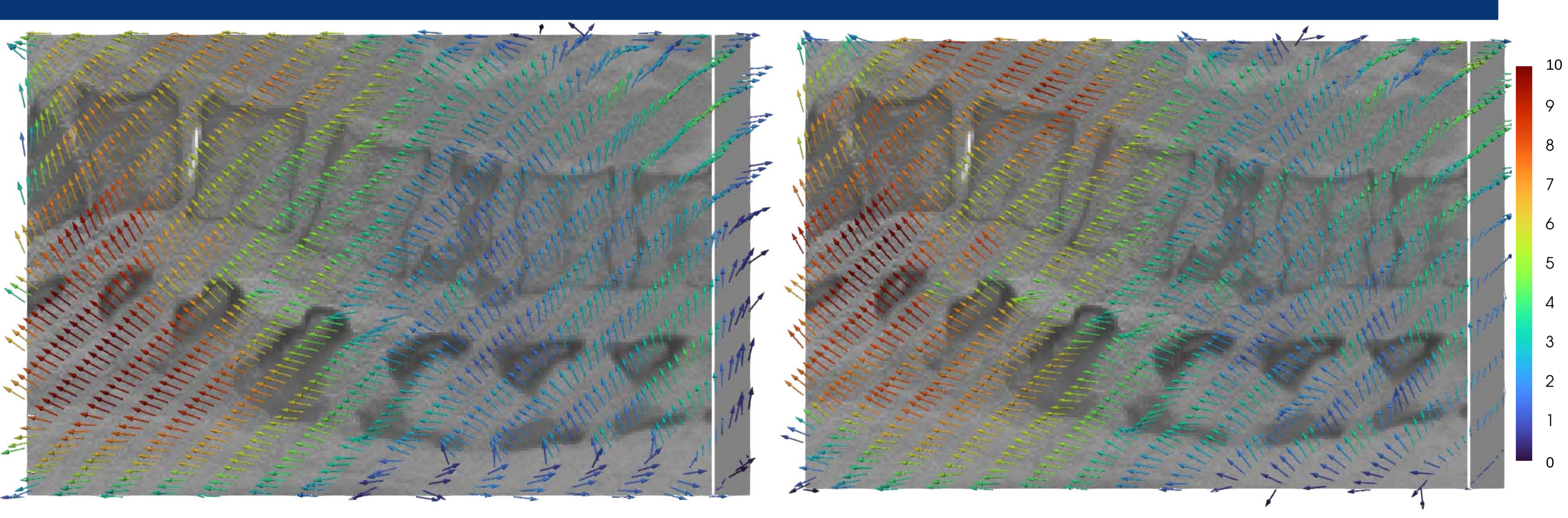
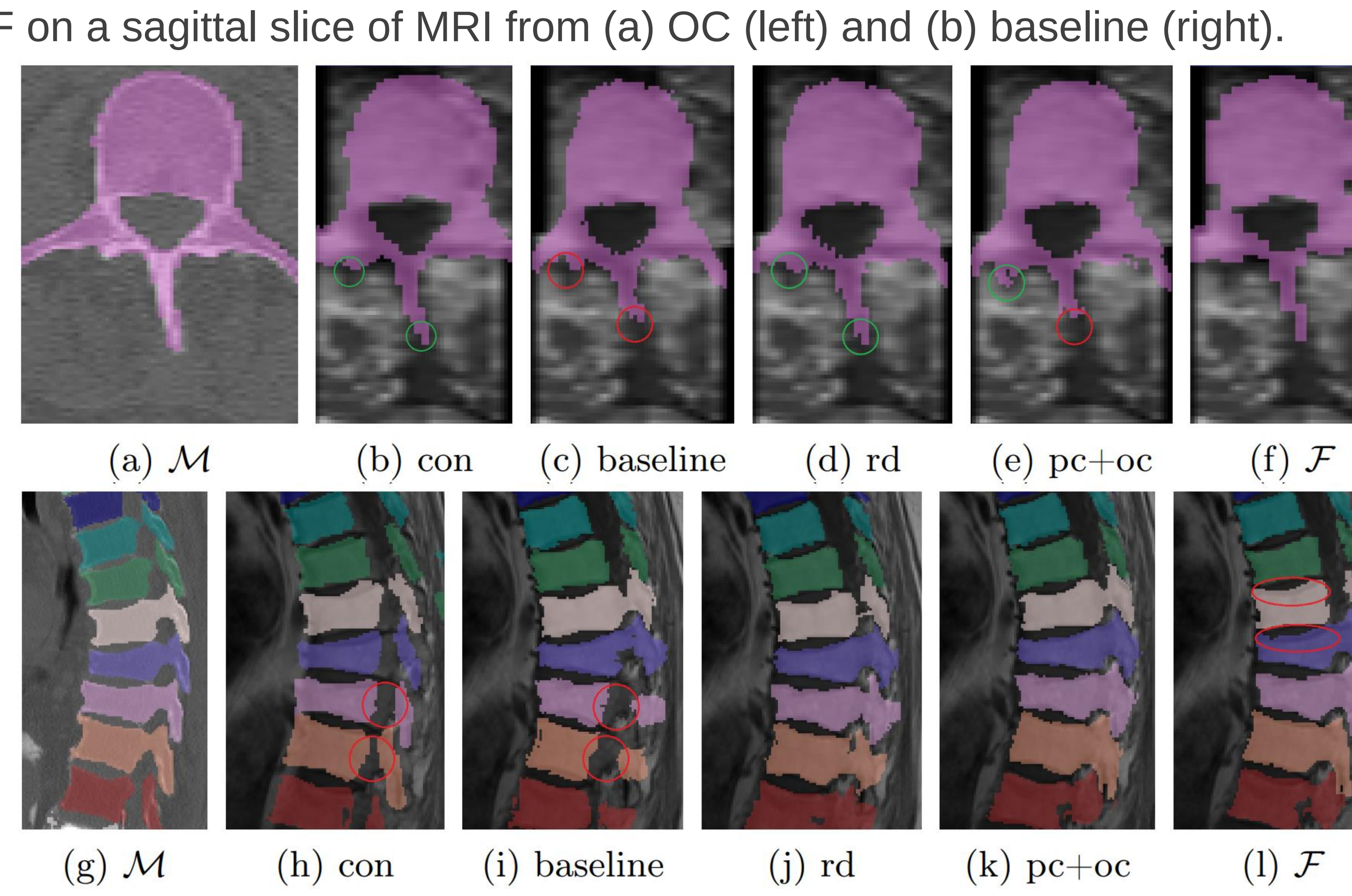


Fig 3. Quiver plots of DDF on a sagittal slice of MRI from (a) OC (left) and (b) baseline (right).

Fig 4. Visual examples of different loss settings



- PC loss contributes significantly to volume preservation, which is beneficial in bone estimation in vertebroplasty or kyphoplasty.
- RD loss achieves the highest level of rigidity (5.7% improvement over baseline), and maintains the details in the process area. It is useful when the image shape should match perfectly, e.g., surgical planning.
- RF loss is a suitable choice when the feasibility of the transformation is more important, e.g., in differential diagnostics.
- OC loss has more consistent displacements inside vertebra area than baseline method. Training with OC loss also decreases PC loss.