Registration of sliding objects using direction dependent B-splines decomposition

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Outline

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   - Overlaps and Gaps Problem
   - Intensity gradient constraint
2. The proposed method
   - Direction dependent B-splines
   - Local orthonormal bases
   - Results

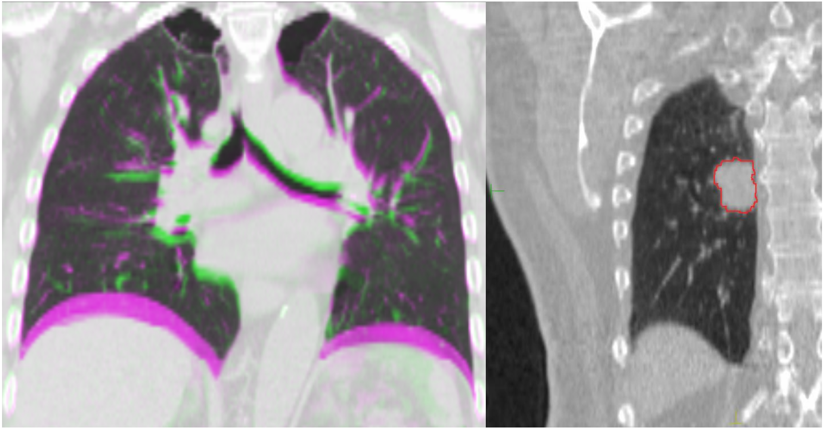
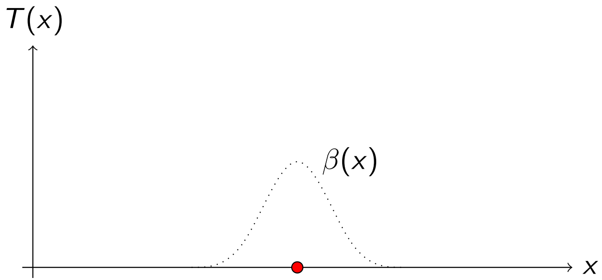


Figure : The end-inhale image, in green, is superimposed on the end-exhale image, in purple.

- Frequently used **basis functions**, e.g. for interpolation,
- Compact support, differentiable, separable, smooth.



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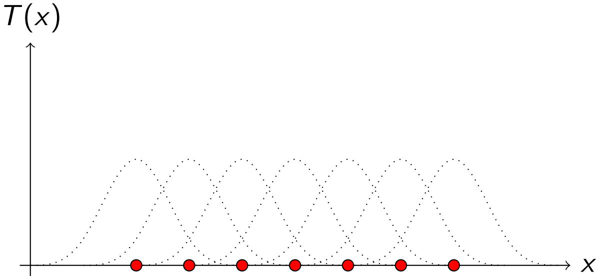

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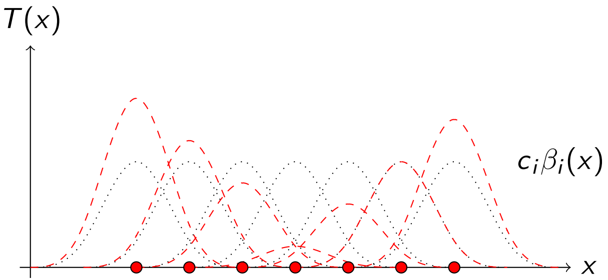

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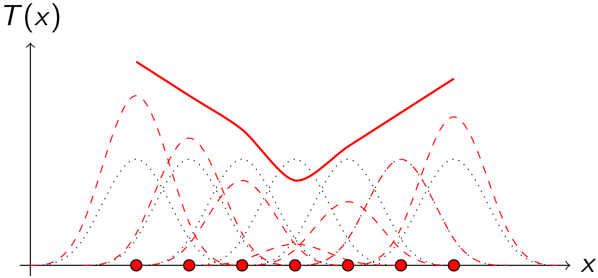

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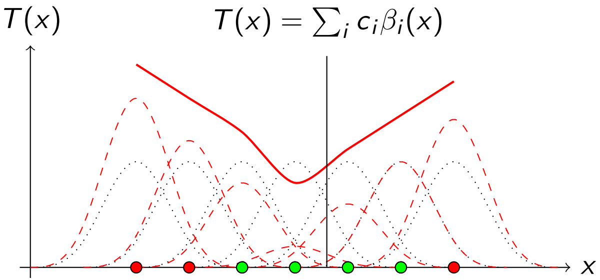

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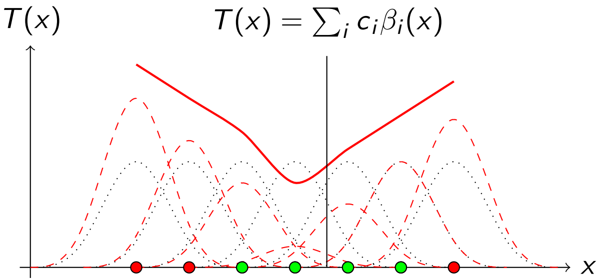


In 3D

- knot points in a 3D grid,
- $c_i \in \mathbb{R}^3$ B-spline coefficients,
- $T(x) \in \mathbb{R}^3$ deformation vector field at $x \in \mathbb{R}^3$.

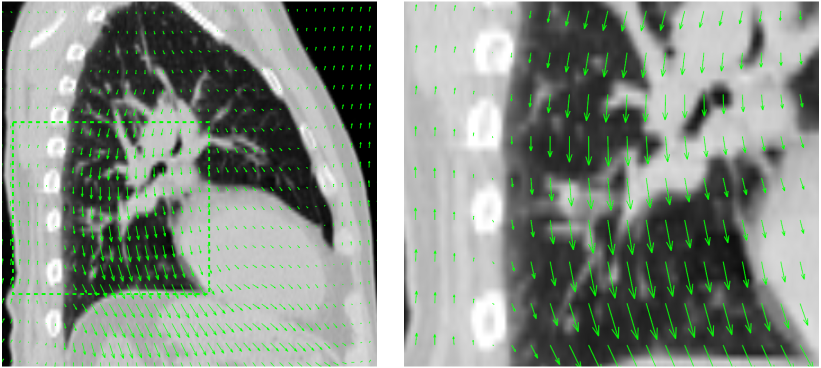
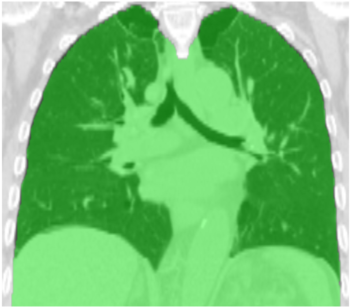


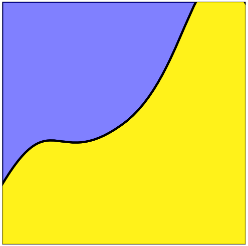
Figure : Example of deformation vector fields obtained after the registration of the end-inhale on the end-exhale phase using a single B-spline

Based on Jef's previous work [Vandemeulebroucke et al., 2012] [Wu et al., 2008].

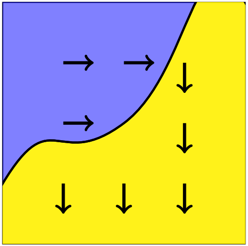
- Thorax registration,
- Motion mask containing the lungs, the mediastinum and the abdomen (Ω),
- The complementary region ($\overline{\Omega}$).



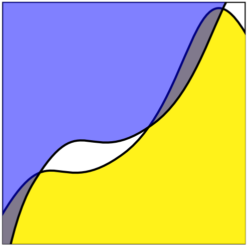
Registering both region separately can lead to overlaps or gaps.



(a) Labels



(b) Vector field

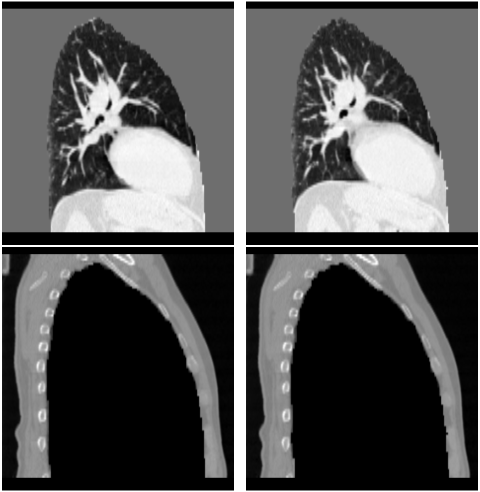


(c) Forward warp

Figure : Illustration of potential issues at a sliding interface when using independent deformation transforms for each regions. The resulting deformation can lead to gaps (white) and overlaps (dark blue).

Wu *et al.* (2008)

- Add high contrast band around regions to register,
- Need consistent segmentation.



1. The breathing motion

2. The proposed method
    - Direction dependent B-splines
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The proposed method is inspired by Schmidt-Richberg's work on Direction-Dependent Regularization [Schmidt-Richberg et al., 2011].

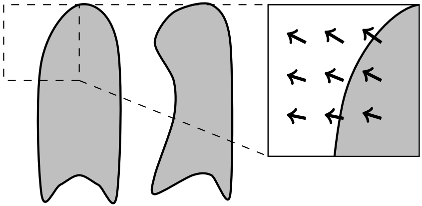


Figure : Normal vector field $\mathcal{N}$.

We decomposed our B-spline deformable registration in three B-spline transforms [Rueckert et al., 1999]:

$$T(x) = \begin{cases} B^N(x) + B^{\Omega}(x) & \text{if } x \in \Omega, \\ B^N(x) + B^{\overline{\Omega}}(x) & \text{if } x \in \overline{\Omega}. \end{cases} \quad (1)$$

with B^N, B^{Ω} and $B^{\overline{\Omega}}$ three constrained cubic B-spline:

$$B^{\overline{\Omega}}(x) = \sum_{i \in J} c_i^{\overline{\Omega}} \boldsymbol{\beta}_i(x), \quad (2)$$

- $x \in \Omega \cup \overline{\Omega}$,
- $i \in J \subset \mathbb{Z}^3$,
- $\boldsymbol{\beta}_i = \prod_j^3 \beta_i^j$.

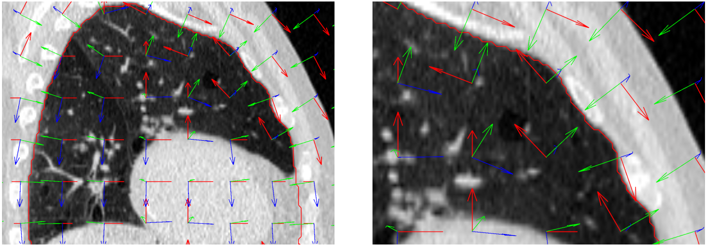


Figure : Local bases $\{N(I(i)), U(I(i)), V(I(i))\}$ superimposed on the corresponding sagittal CT slice of a thorax. N, U and V are in green, red and blue, respectively

$$
\begin{aligned}
U(I(i)) &= N(I(i)) \otimes \hat{w}_i \\
V(I(i)) &= N(I(i)) \otimes U(I(i))
\end{aligned}
$$

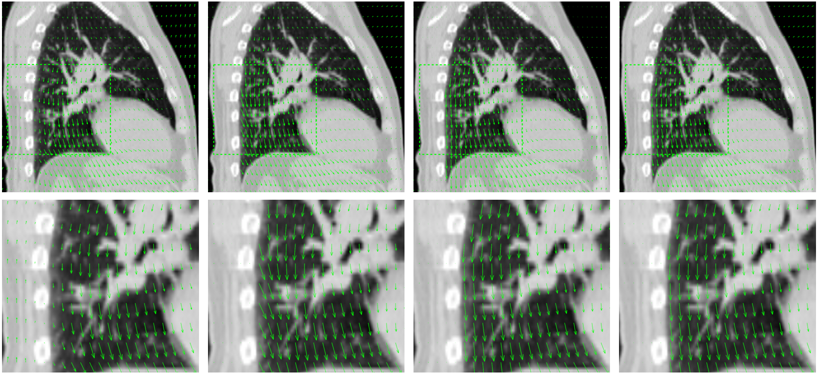
$$\hat{w}_i = \underset{w \in \{e_x, e_y, e_z\}}{\text{argmin}} \|N(I(i)) \cdot w\|$$

5 parameters per knot points $p_i^N, p_i^{\Omega,U}, p_i^{\Omega,V}, p_i^{\overline{\Omega},U}, p_i^{\overline{\Omega},V}$:

$$\begin{cases} c_i^N = p_i^N N(I(i)) \\ c_i^{\Omega} = p_i^{\Omega,U} U(I(i)) + p_i^{\Omega,V} V(I(i)) \\ c_i^{\overline{\Omega}} = p_i^{\overline{\Omega},U} U(I(i)) + p_i^{\overline{\Omega},V} V(I(i)) \end{cases} \tag{3}$$

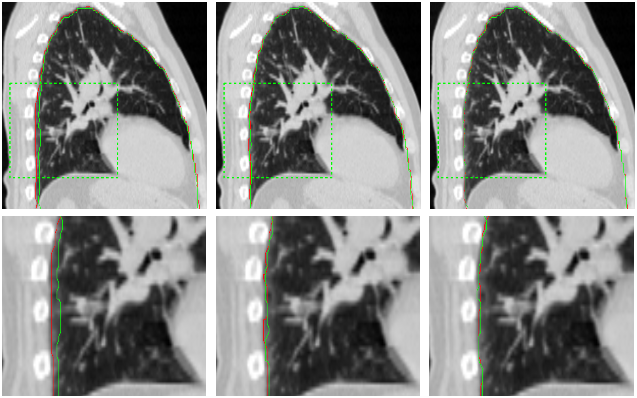
Partial derivatives are projected on the same base during the optimization process:

$$\begin{cases} \frac{\partial T(x)}{\partial p_i^N} = \frac{\partial B^N(x)}{\partial c_i^N} \cdot N(I(i)), \\ \frac{\partial T(x)}{\partial p_i^{\Omega,U}} = \frac{\partial B^\Omega(x)}{\partial c_i^\Omega} \cdot U(I(i)), \\ \frac{\partial T(x)}{\partial p_i^{\Omega,V}} = \frac{\partial B^\Omega(x)}{\partial c_i^\Omega} \cdot V(I(i)), \\ \frac{\partial T(x)}{\partial p_i^{\overline{\Omega},U}} = \frac{\partial B^{\overline{\Omega}}(x)}{\partial c_i^{\overline{\Omega}}} \cdot U(I(i)). \\ \frac{\partial T(x)}{\partial p_i^{\overline{\Omega},V}} = \frac{\partial B^{\overline{\Omega}}(x)}{\partial c_i^{\overline{\Omega}}} \cdot V(I(i)). \end{cases} \quad (4)$$



(a) (b) (c) (d)

Figure : Example of deformation vector fields obtained after registration using a single B-spline (a), multiple B-spline without sliding constraint (b), Wu *et al.*'s method (c) and multiple B-spline with sliding constraint (d).



(a) (b) (c)

Figure : The motion mask interface deformed with the inside deformation (green) and the outside deformation (red) using one B-spline per region (a), using Wu *et al.*'s method (b) and using the proposed method (c).

Results obtained on 16 patients:

- 10 with 300 landmarks
- 6 with 100 landmarks

TRE (in mm)

Before	:	8.4 ± 5.6
Single B-spline	:	3.7 ± 4.0
Multi B-splines	:	1.43 ± 1.1
Wu *et al.*	:	1.35 ± 1.0
The proposed method	:	1.49 ± 1.2

Gaps and Overlaps (in cm^3)

Multi B-spline	:	167 ± 76 / 51 ± 22
Wu *et al.*	:	91 ± 26 / 54 ± 22
The proposed method	:	82 ± 24 / 57 ± 22

This work is implemented in

elastix: a toolbox for intensity-based medical image registration. [Klein et al., 2010]

Conference

Pulmonary Image Analysis part of MICCAI's workshops,

Journal

Physics Medicine and Biology (second review)

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