LABORATORY OF OPTICS AND EXPERIMENTAL MECHANICS

Computational Registration of Biomedical Data towards More Effective Image Analysis

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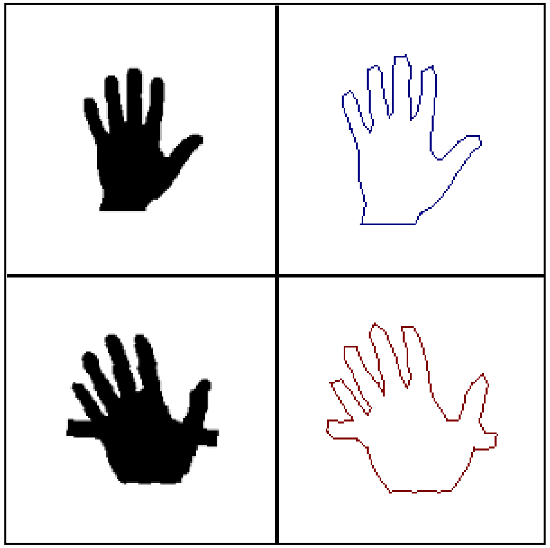
Outline

1. Introduction
2. Methods
   a) Spatial Registration of (2D & 3D) Images
   b) Spatio & Temporal Registration (registration of 2D image sequences)
3. Applications and Results
   a) Plantar Pressure Images (2D & 2D image sequences)
   b) Medical Images (2D & 3D)
4. Conclusions

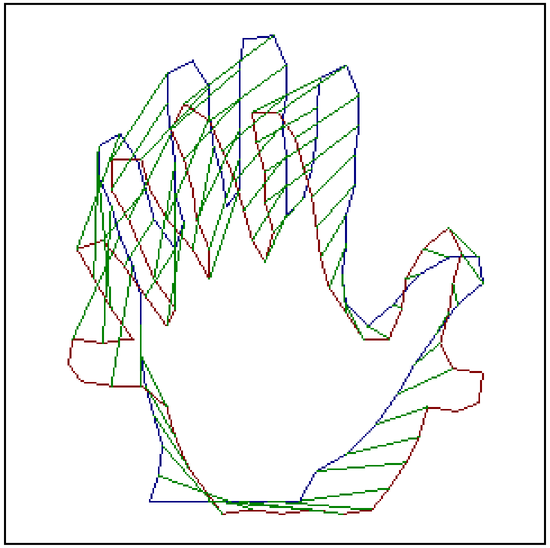
Introduction: Matching and Registration of Images

Image Matching

Image matching is **the process of establishing correspondences between objects** in images



Original images and contours



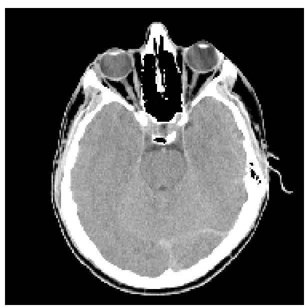
Some of the correspondences found

Bastos & Tavares (2006) Inverse Problems in Science and Engineering 14(5):529-541
Oliveira, Tavares, Pataky (2009) VipMAGE 2009, pp. 269-274

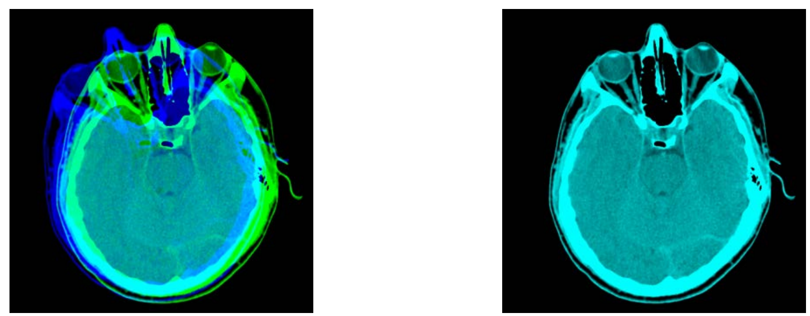
Image Registration

Image registration is the **process of searching for the best transformation that change one image in relation to another image** in order to correlated features assume similar locations in a common space

Template (or fixed) image



Source (or moving) image



Overlapped images before and after the registration

Oliveira & Tavares (2012) Computer Methods in Biomechanics and Biomedical Engineering, DOI:10.1080/10255842.2012.670855

Image Registration

Applications

- **Facilitate image-based diagnosis**
  - Fusion of images from different imaging modalities (CT/PET, MRI/CT, SPECT/CT, MRI/PET, …)
  - Follow-up of pathologies
- **Support surgical interventions** (more efficient localization of lesions, find alignments between devices and patients, etc.)
- **Optimization of radio-therapeutic treatments**
- **Automatic recognition of organs/tissues** (e.g. support complex tasks of image segmentation and identification)
- **Building of Atlas** (with well-known cases used for comparison)
- **Simplify posterior statistical analysis** (e.g. SPM, Z-scores, etc.)
- …

Image Registration

In the last years, considerable research has been done concerning biomedical data registration. The **methodologies can be classified based on** different criteria:

- **Data dimensionality: 2D/2D, 2D/3D, 3D/3D, 2D/3D+Time**
- **Features used: extrinsic** (using features external to the patient) or **intrinsic** (using information from the patient; e.g. pixel intensity values, relevant points, contours, regions, skeletons, surfaces, …)
- **Interaction: manual, semiautomatic or automatic**
- **…**

Image Registration

(Cont.)

- **Transformation type: rigid, similarity, affine, projective, curved**
- **Transformation domain: local** or **global**
- **Modalities involved: same modality** (CT/CT, MRI/MRI, PET/PET, …), **different modalities** (CT/MRI, MRI-T1/MRI-T2, PET/CT, …) or **patient/model** (e.g. between a patient and an atlas or between a patient and a device)
- **Subjects:** registration of images from the **same subject** or from **different subjects**, or images of a subject with images in an **atlas**
- **Organs/tissues involved:** brain, liver, etc.
- ...

Oliveira & Tavares (2012) Computer Methods in Biomechanics and Biomedical Engineering, DOI:10.1080/10255842.2012.670855

Image Registration

In the registration of image data, **similarity measures based on pixel intensity values are commonly used; e.g.:**

- Cross-Correlation (CC) and related measures

$$\mathrm{CC}_{fg} = \sum_i f(i) g(i)$$

- Sum of Squared Differences (SSD) and correlated measures, like the Mean Squared Error (MSE)

$$\mathrm{SSD}_{fg} = \sum_i \left(f(i) - g(i) \right)^2 \qquad \mathrm{MSE}_{fg} = \frac{1}{N} \sum_i \left(f(i) - g(i) \right)^2$$

- Mutual Information (MI) and derived measures

$$\mathrm{MI} = H(f) + H(g) - H(f,g)$$

where $H(f)$ and $H(g)$ are the Shannon's entropy of f and g images, and $H(f,g)$ the Shannon's entropy of the joint histogram of f and g

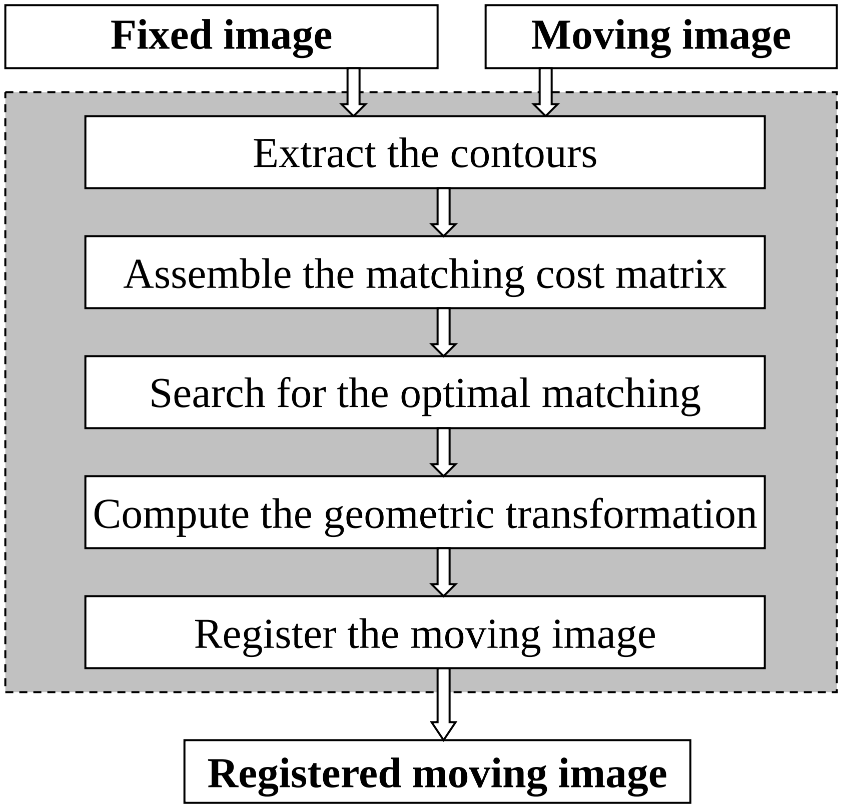
Image Registration

In the last years, **we have been developing methods for biomedical image data matching and registration** based on different techniques and applied them in several applications

- **Techniques**
  - Based **on features** (points, contours) extracted from the images and based **on the intensity of the pixels** (or voxels)
  - By **computing the optimal registration transformation directly or iteratively**
  - By **using different transformation models**
- **Data**
  - Images **from the same patient and from different patients**
  - Images **from the same or different modalities**
  - Registration of **2D and 3D images, and of 2D image sequences**

Methods: Spatial Registration of 2D and 3D images

Registration **based on Contours Matching**



The **cost matrix is built based on geometric or physical principles**

The **matching is found based on the minimization of the sum of the costs associated to the possible correspondences**

To search for the best matching is used an optimization assignment algorithm based on the Hungarian method, simplex method, graphs or dynamic programming

Bastos & Tavares (2006) Inverse Problems in Science and Engineering 14(5):529-541
Oliveira & Tavares (2009) Computer Modeling in Engineering & Sciences 43(1):91-110
Oliveira, Tavares, Pataky (2009) Journal of Biomechanics 42(15):2620-2623

Registration **based on Direct Maximization of the Cross-Correlation (CC)**

Assumption: The higher the cross-correlation between the pixel intensity values of the two images, the better the registration

Cross-correlation between I_0 and I_1 in function of a shift a:

$$CC_{I_0 I_1}(a) = \int I_0(x) I_1(x-a) dx$$

It can be written as a convolution:

$$CC_{I_0 I_1}(a) = \int I_0(x) \bar{I}_1(a-x) dx = \{I_0 * \bar{I}_1\}(a)$$

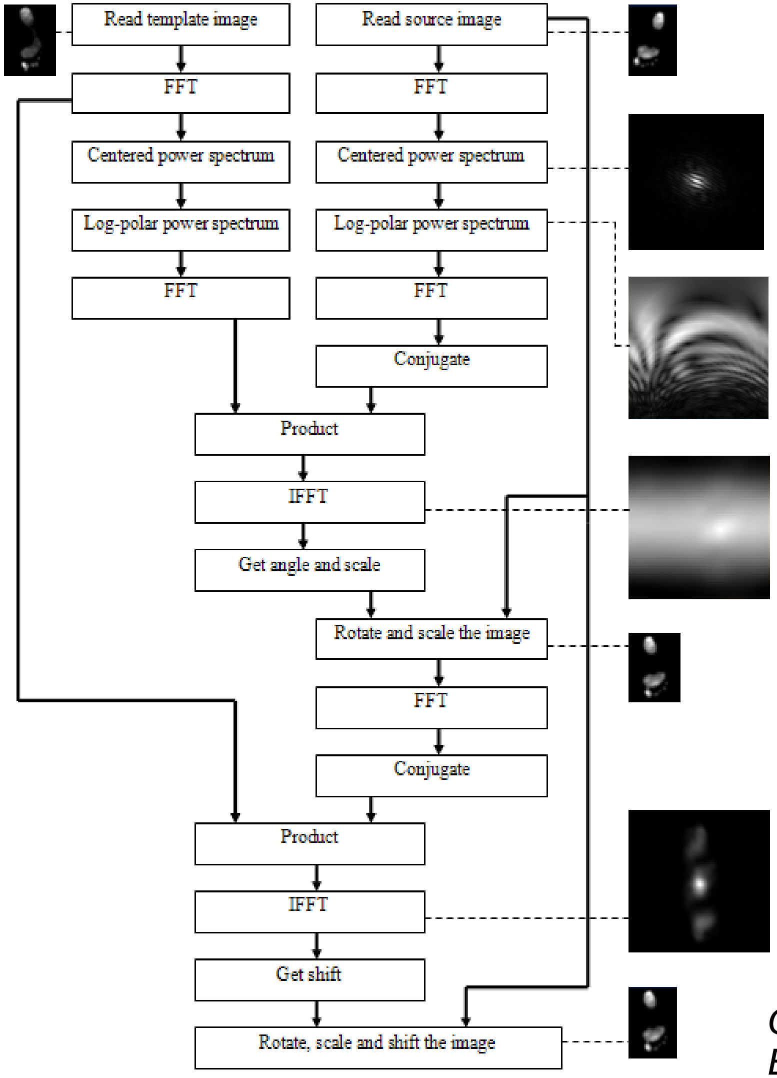
And from the convolution Theorem, one have:

$$\mathcal{F}\{I_0 * \bar{I}_1\} = \mathcal{F}\{I_0\} \mathcal{F}\{\bar{I}_1\}$$

Thus, **computing the product of the Fourier transform of I_0 and $\bar{I}_1$ and then its inverse Fourier transform, the cross-correlation can be obtained for all shifts**

($*$ represents the convolution operation and $\mathcal{F}$ the Fourier transform)

Registration **based on Direct Maximization of the CC**



The scaling and rotation are obtained from the spectrum images after their conversion to the log-polar coordinate system

The fundament of this methodology is to search for the geometric transformation involved using the shift, scaling and rotation properties of the Fourier transform

Oliveira, Pataky, Tavares (2010) Computer Methods in Biomechanics and Biomedical Engineering 13(6):731-740

Registration **based on Direct Minimization of the Sum of Squared Differences (SSD)**

Assumption: The lower the sum of the squared differences between the pixel intensity values of the two images, the better registered the images

Sum of squared differences between I_0 and I_1 in function of a shift a:

$$SSD_{I_0 I_1}(a) = \int \left(I_0(x) - I_1(x-a)\right)^2 dx$$

This equation can be written as:

$$SSD_{I_0 I_1}(a) = \int I_0^{\,2}(x)dx + \int I_1^{\,2}(x-a)dx - 2\int I_0(x) I_1(x-a)dx$$

The first two terms can be directly evaluated, and the third term can be transformed into a convolution and then efficiently evaluated using the Fourier transform

The algorithm implemented is quite similar to the Cross-Correlation based algorithm; the main difference is the similarity measure used

Oliveira, Pataky, Tavares (2010) Computer Methods in Biomechanics and Biomedical Engineering 13(6):731-740

Registration **based on the Phase Correlation Technique**

This technique is basically based on the shift property of the Fourier transform:

If $$I_1(x) = I_0(x - x_0)$$

then $$\mathcal{F}\{I_1(x)\}(u) = e^{-2i\pi u x_0}\,\mathcal{F}\{I_0(x)\}(u)$$

To estimate the shift between the input images, the inverse of the Fourier transform of the cross-power is computed:

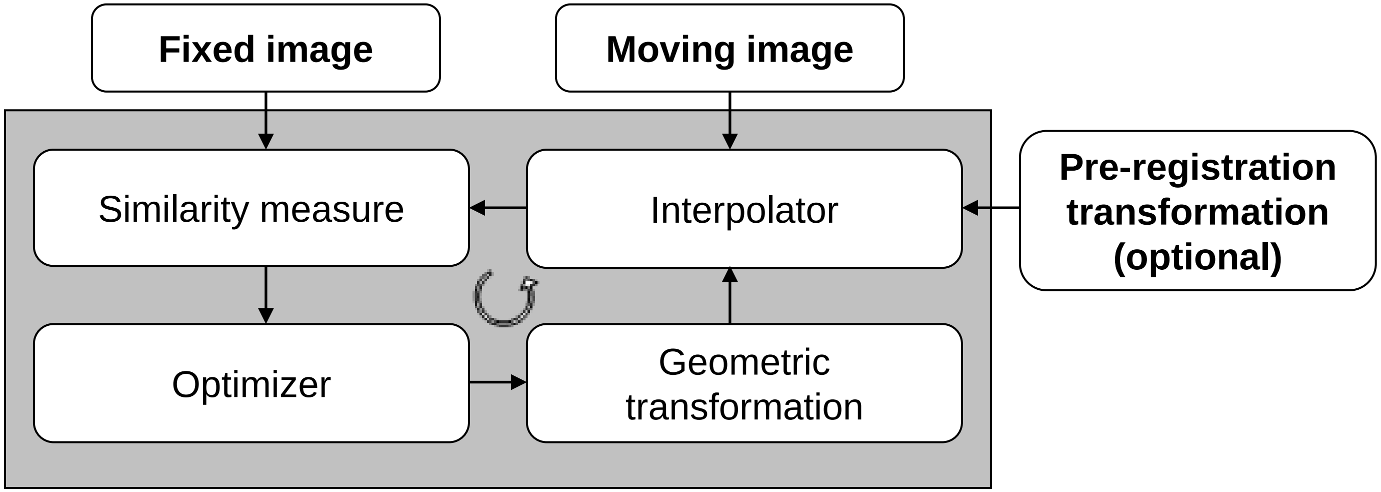
Cross-power: $$\frac{\mathcal{F}\{I_0\}\,\mathcal{F}^*\{I_1\}}{\left|\mathcal{F}\{I_0\}\,\mathcal{F}^*\{I_1\}\right|} = e^{2i\pi u x_0}$$ (the * represents the complex conjugate)

The algorithm implemented is also similar to the cross-correlation based algorithm

Oliveira, Pataky, Tavares (2010) Computer Methods in Biomechanics and Biomedical Engineering 13(6):731-740

Registration **based on Iterative Optimization**

Fundaments: This methodology **is based on the iterative search for the parameters of the transformation that optimizes a similarity measure** between the input images

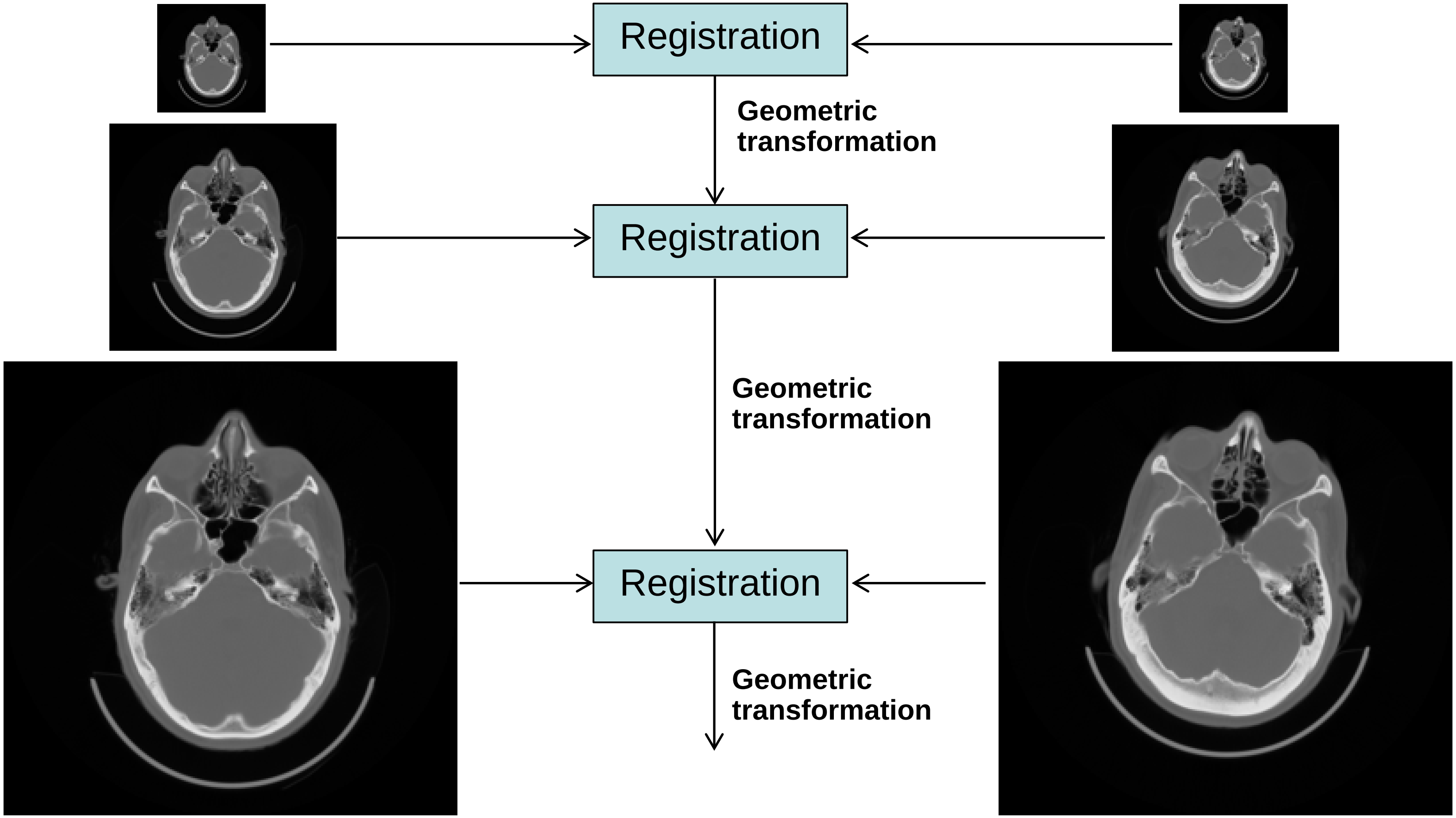


The optimization algorithm stops when a similarity criterion is achieved

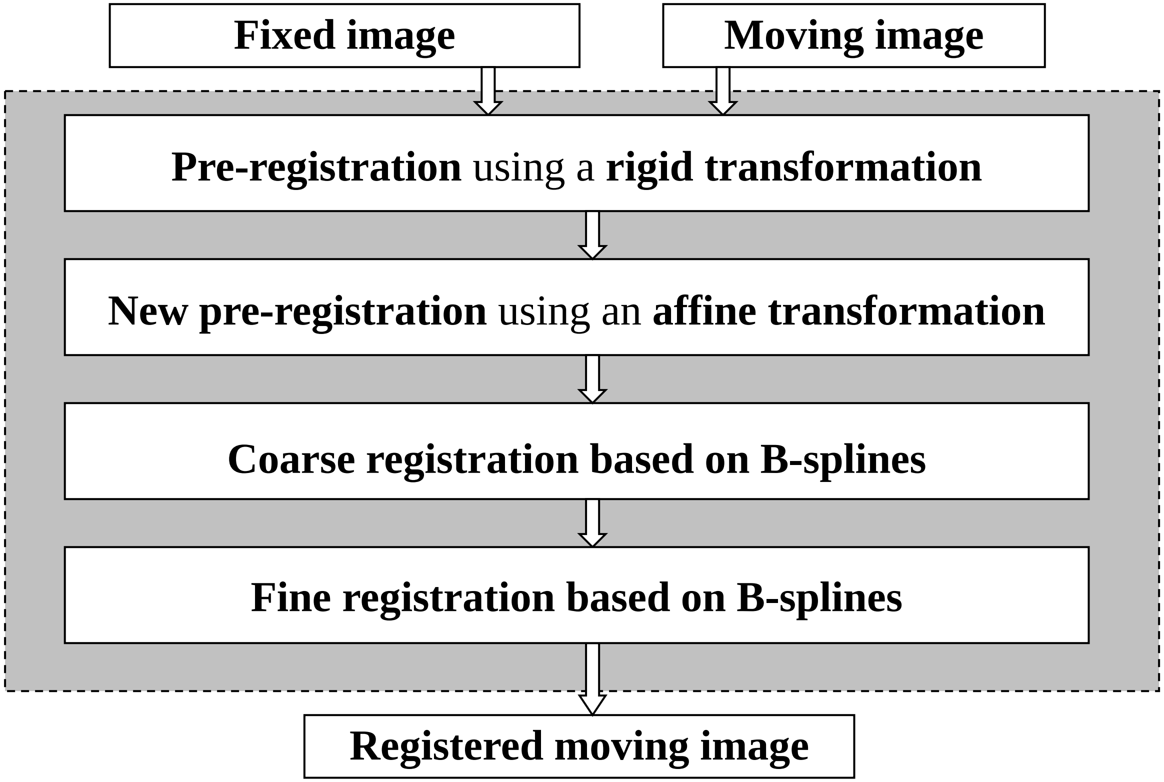
Oliveira & Tavares (2012) Computer Methods in Biomechanics and Biomedical Engineering, DOI:10.1080/10255842.2012.670855

Registration **based on Iterative Optimization**

To speedup the computational process, the **multi-resolution strategy is frequently used**

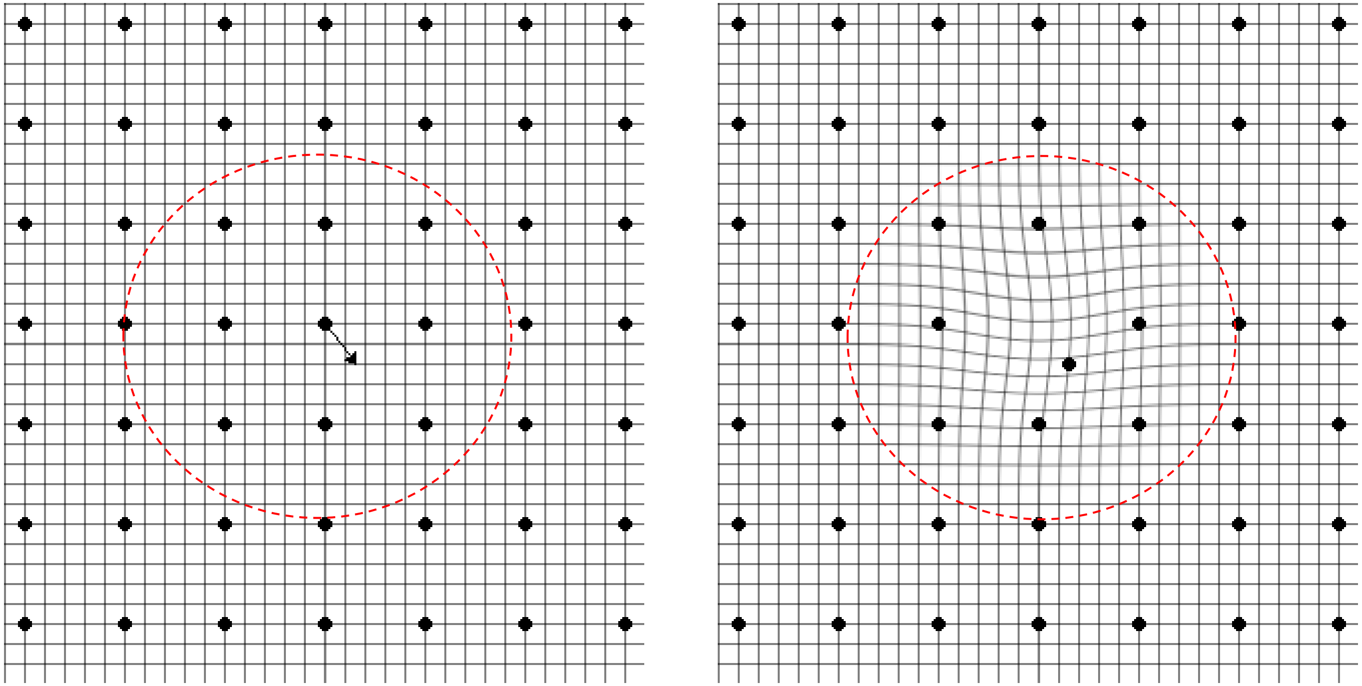


Registration **using Iterative Optimization and a curved transformation based on B-splines**



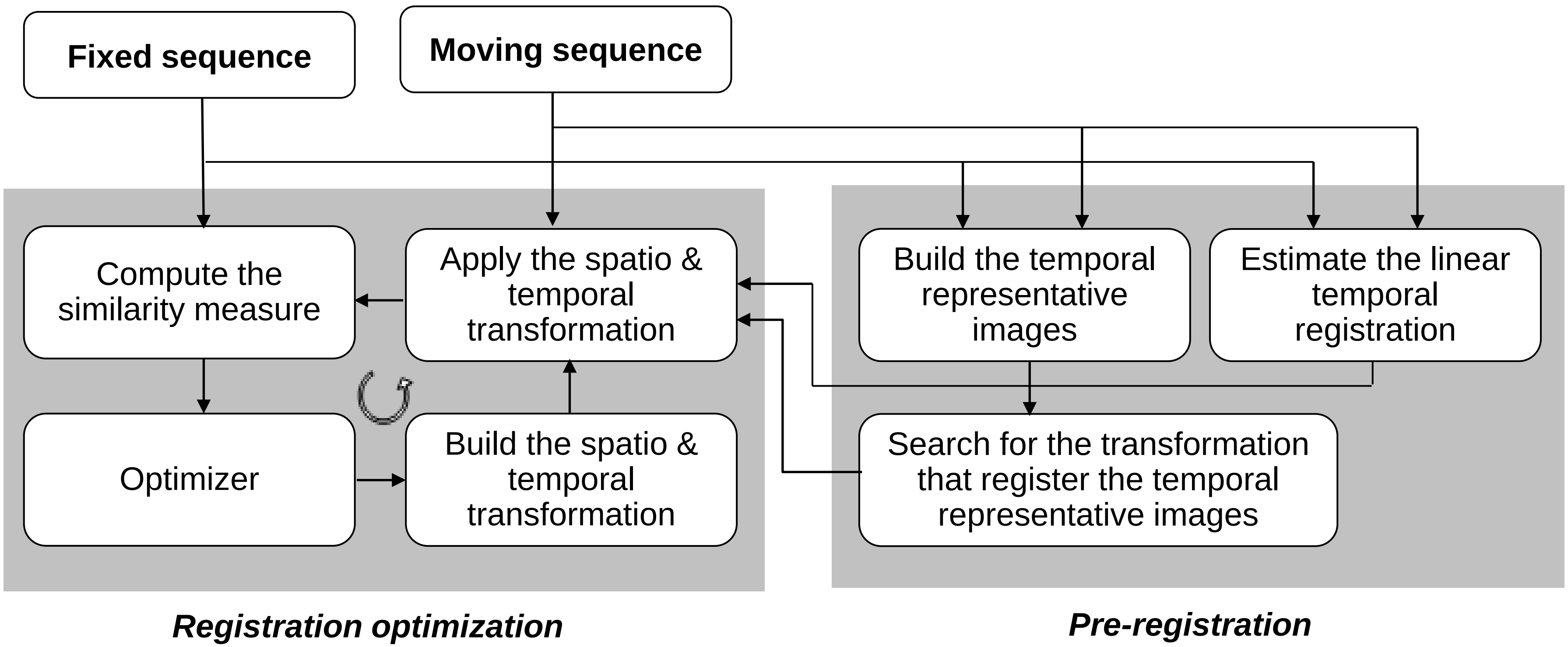
Registration **using Iterative Optimization and a curved transformation based on B-splines**

The registration based on B-splines is of the **free-form deformation type**: **The deformation is locally defined based on the localization associated to the grid knots**; **if the localization of a knot changes, then all pixels under its influence are moved accordingly to** the B-spline type



Methods: Spatio & Temporal Registration

Spatio & Temporal registration of image sequences



Oliveira, Sousa, Santos, Tavares (2011) Medical & Biological Engineering & Computing 49(7):843-850

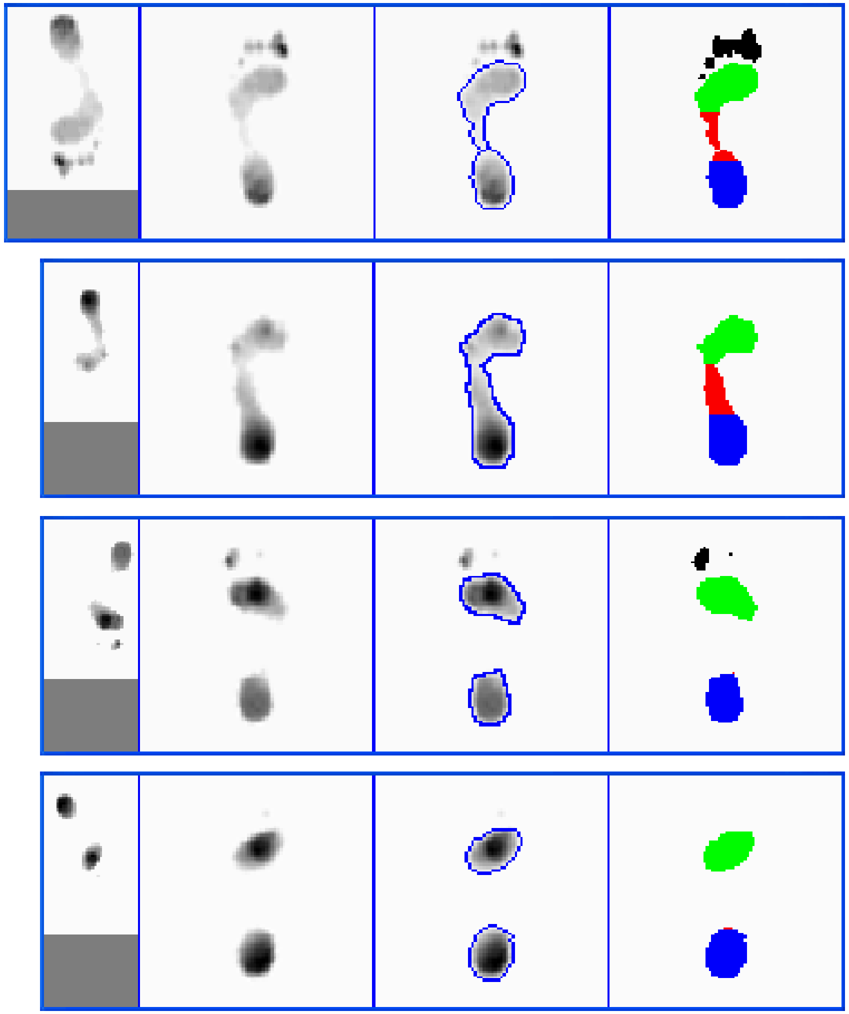
Oliveira & Tavares (2012) Medical & Biological Engineering & Computing DOI:10.1007/s11517-012-0988-3

Applications and Results: Plantar Pressure Images

Applications in Plantar Pressure Images Studies

A computational solution, device independent, **has been developed to assist studies based on the registration of plantar pressure images**:

- Foot segmentation
- Foot classification: left/right, high arched, flat, normal, …
- Foot axis computation
- Footprint indices computation
- Posterior statistical analysis



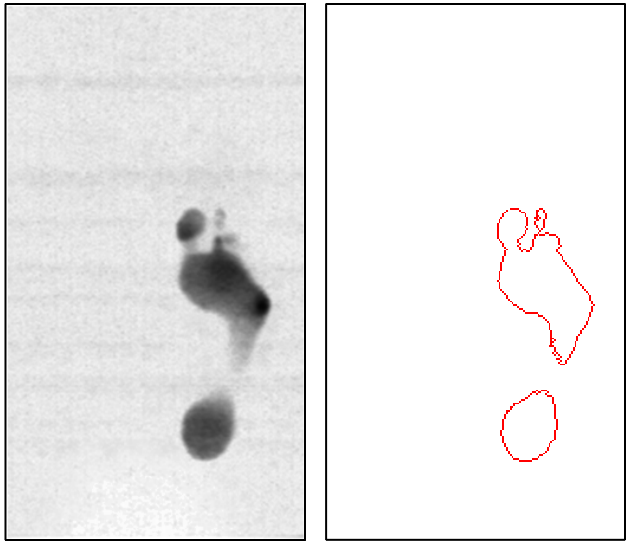
Oliveira, Sousa, Santos, Tavares (2012) Computer Methods in Biomechanics and Biomedical Engineering 15(11):1181-1188

Registration **based on Contours Matching**

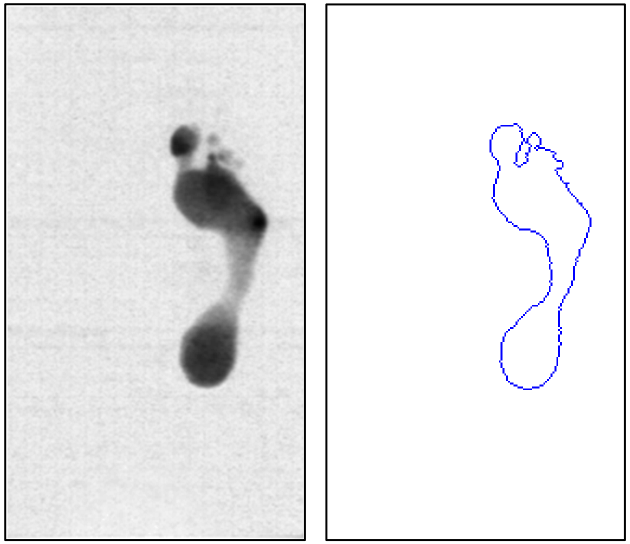
Example 1

I - Contours extraction and matching

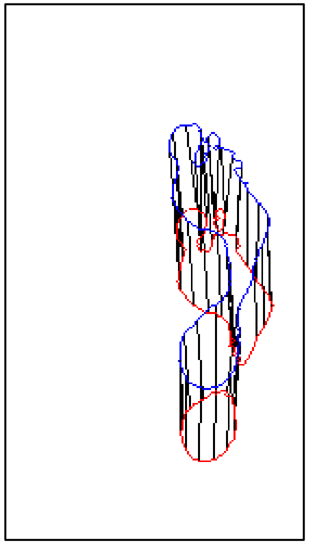
Fixed image and contour (optical plantar pressure device)



Moving image and contour (optical plantar pressure device)



Matching established



Registration **based on Contours Matching**

Example 1 (cont.)

II - Registration

Registration: 2D, monomodal, intrasubject

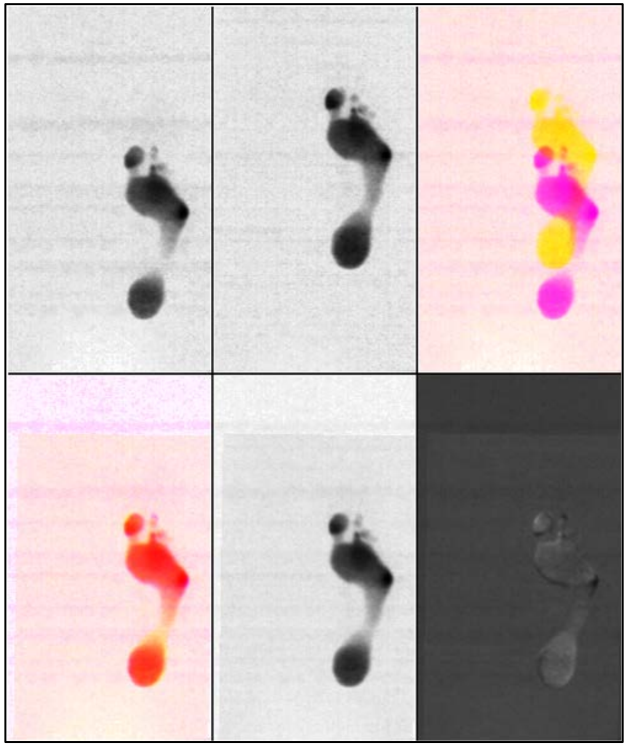
Processing time: 0.125 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

Images dimensions: 160x288 pixels

Moving image

Fixed image

Overlapped images before the registration



Overlapped images after registration

Difference of the images after the registration

Sum of the images after the registration

Registration **based on Direct Maximization of the CC**

Examples 2 & 3

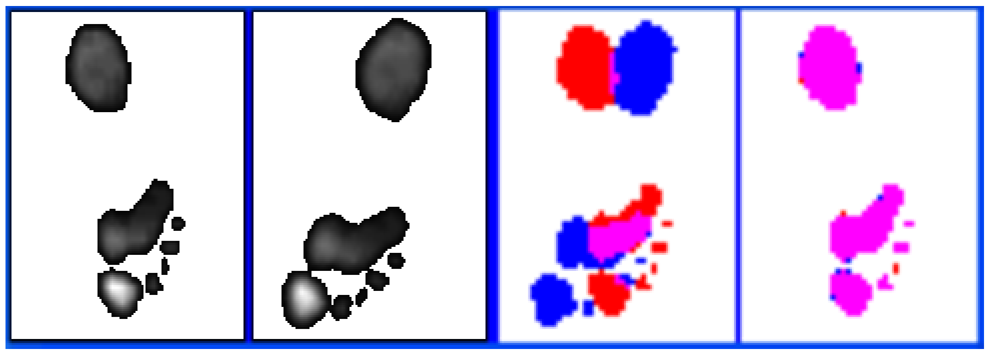
Image acquisition device: Footscan

Registration: 2D, monomodal, intrasubject (on the top) and intersubject (on the bottom)

Processing time: 0.04 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

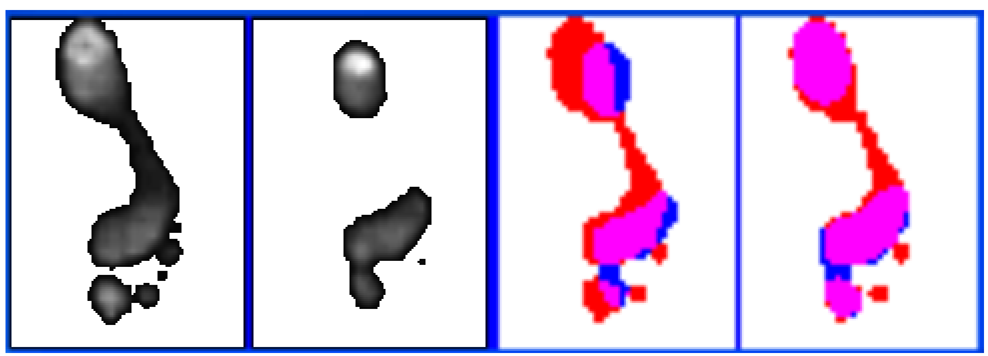
Images dimensions: 45x63 pixels

Fixed image | ***Moving image*** | ***Overlapped images before and after the registration***



Images from the same foot

Using a **rigid transformation**



Images from different feet

Using a **similarity transformation**

Spatio & Temporal registration of Plantar Pressure Image Sequences

Example 1

Device: EMED (25 fps, resolution: 2 pixels/cm^2, images dimensions: 32x55x13; 32x55x18)

Registration: rigid (spatial), polynomial (temporal); similarity measure: MSE

Processing time: 4 s - AMD Turion64, 2.0 GHz, 1.0 GB of RAM

	Fixed sequence	***Moving sequence***	***Overlapped sequences***
Before the registration			
After the registration			

Spatio & Temporal registration of Plantar Pressure Image Sequences

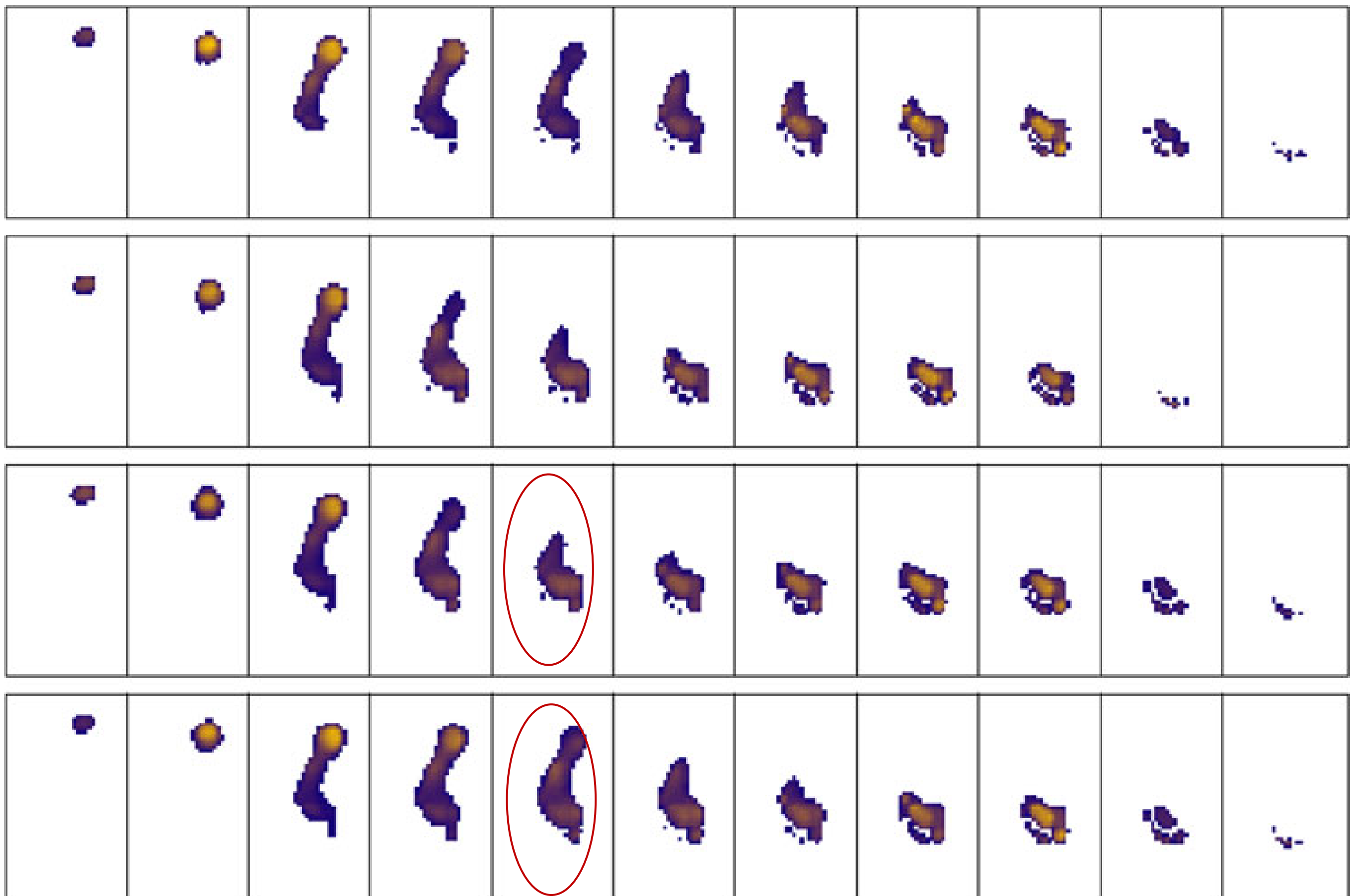
Example 2

Fixed sequence

Moving sequence

Registered moving sequence using a polynomial temporal transf. of 1st degree

Registered moving sequence using a polynomial temporal transf. of 4th degree



Applications and Results: Medical Images

Registration **based on Contours Matching**

Example 1

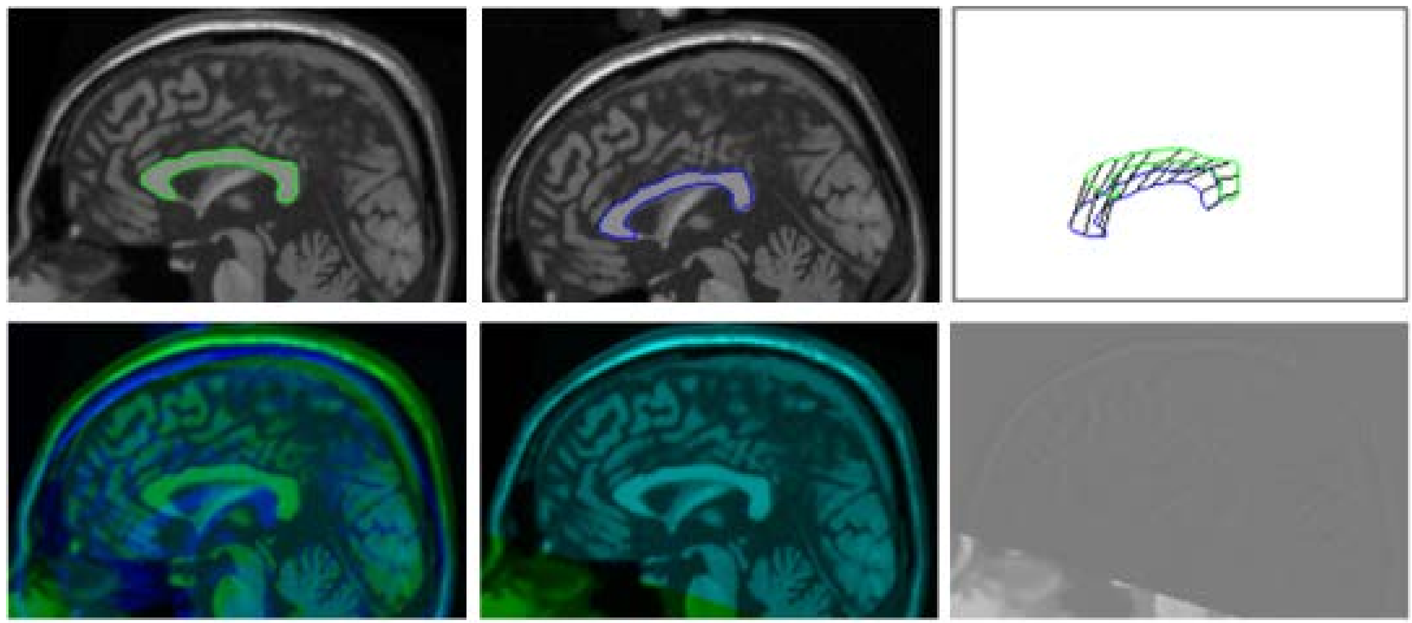
Registration based on the matching of the Corpus Callosum contours

Registration: 2D, monomodal, intrasubject

Processing time: 0.5 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

Images dimensions: 217x140 pixels

Fixed image and contour (MRI) | ***Moving image and contour (MRI)*** | ***Matching found***



Overlapped images before the registration | ***Overlapped images after the registration*** | ***Difference between the images after the registration***

Registration **based on Direct Maximization of the CC**

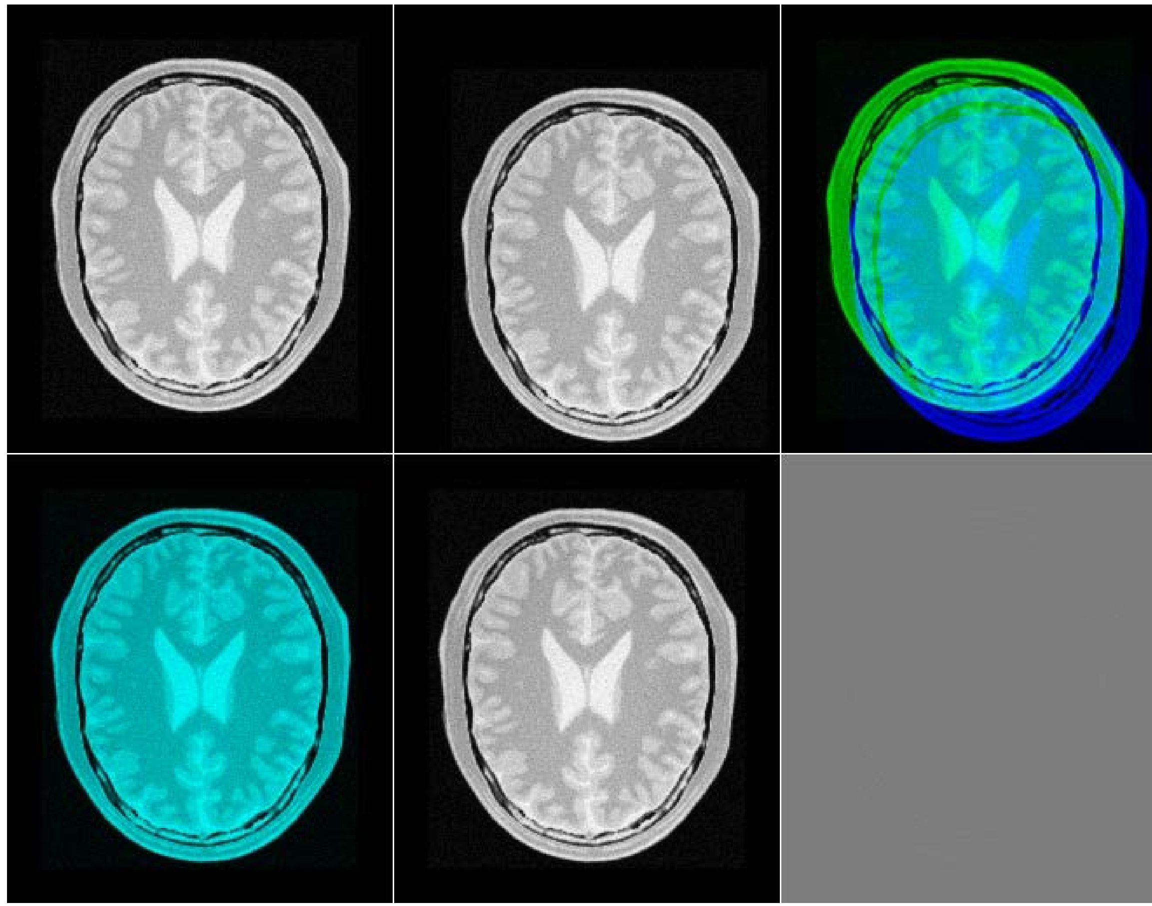
Example 2

Registration: 2D, monomodal, intrasubject

Processing time: 2.1 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

Images dimensions: 221x257 pixels

Fixed image MRI (proton density) | ***Moving image MRI (proton density)*** | ***Overlapped images before the registration***



Overlapped images after the registration | ***Sum of the images after the registration*** | ***Difference of the images after the registration***

Registration **based on Iterative Optimization**

Example 3

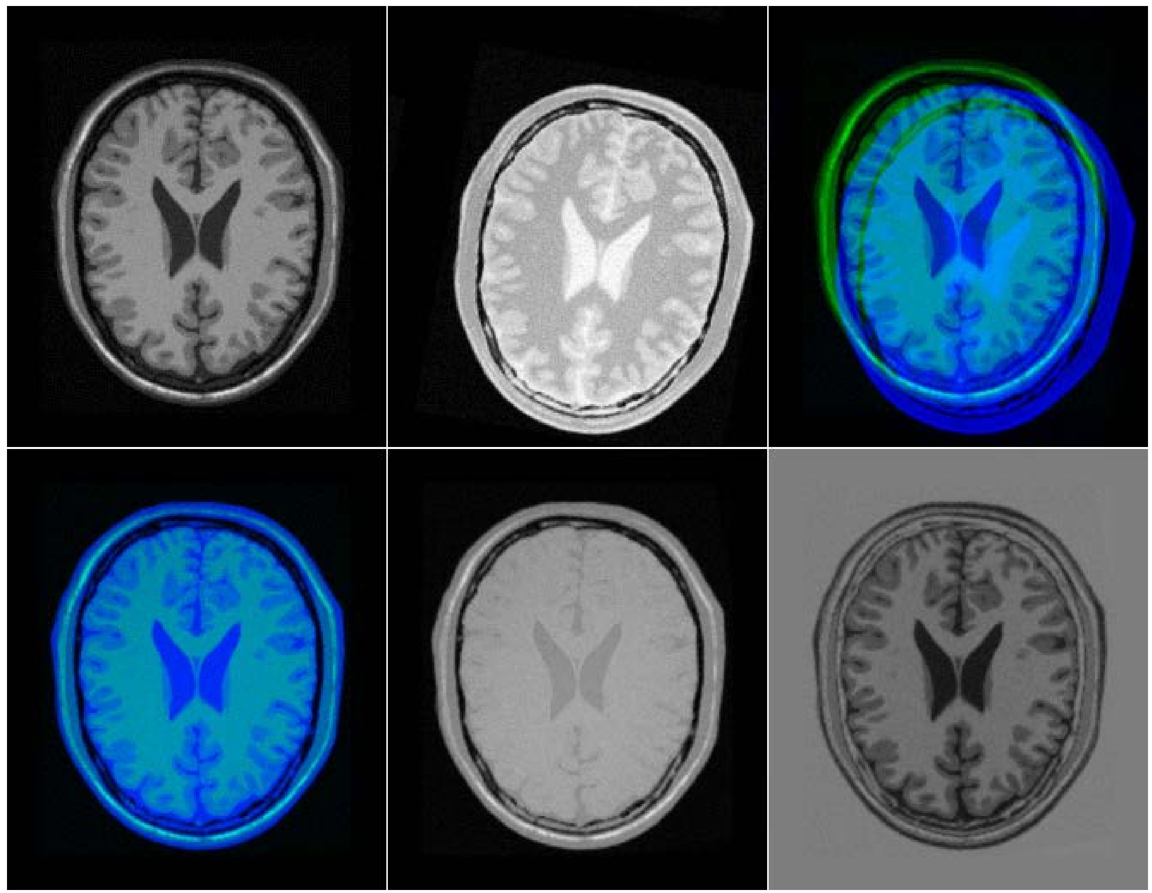
Registration: 2D, multimodal, intrasubject (without pre-registration)

Similarity measure: MI

Processing time: 5.4 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

Images dimensions: 221x257 pixels

Fixed image (MRI - T1) | ***Moving image (MRI - proton density)*** | ***Overlapped images before the registration***



Overlapped images after the registration | ***Sum of the images after the registration*** | ***Difference of the images after the registration***

Registration **based on Iterative Optimization**

Example 4

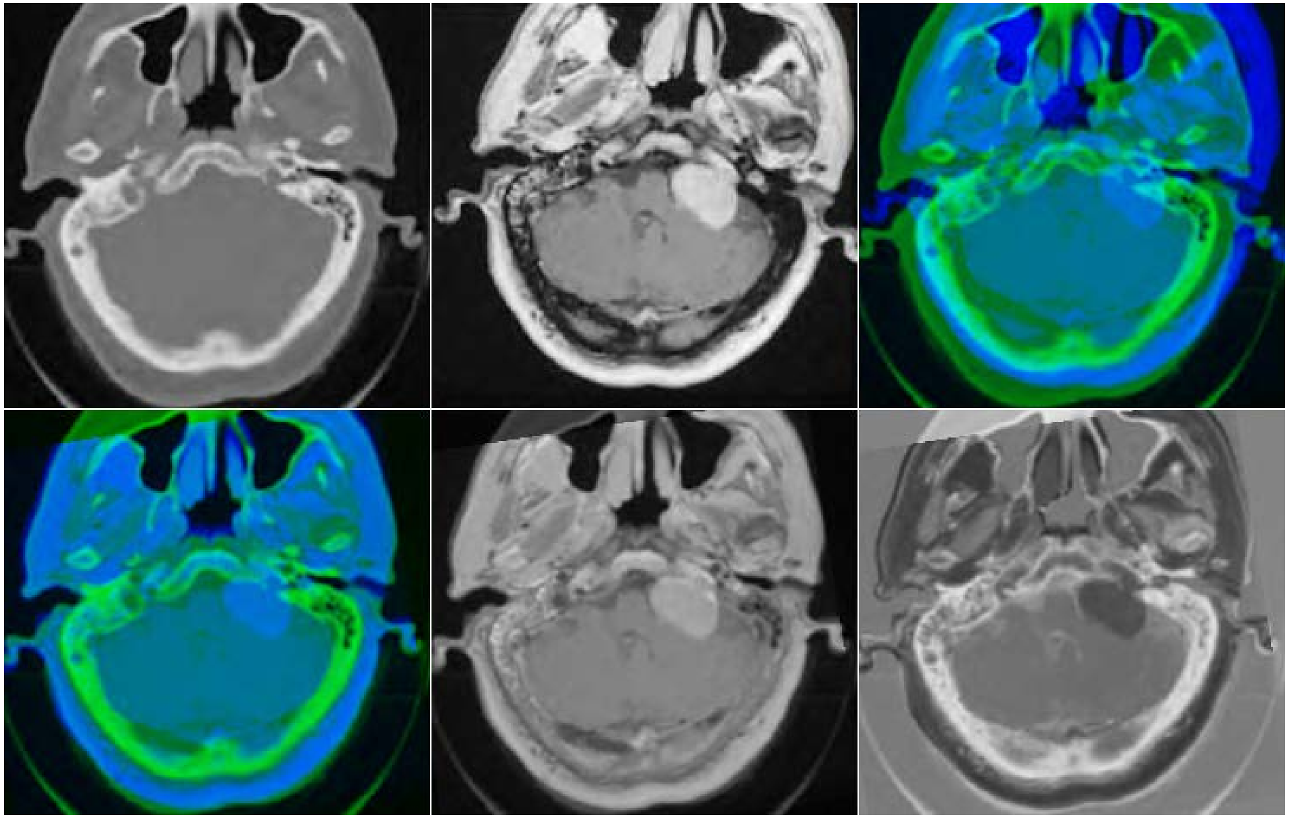
Registration: 2D, multimodal, intrasubject (without pre-registration)

Similarity measure: MI

Processing time: 4.6 s (AMD Turion64, 2.0 GHz, 1.0 GB of RAM)

Images dimensions: 246x234 pixels

Fixed image (CT) | ***Moving image (MRI)*** | ***Overlapped images before the registration***



Overlapped images after the registration | ***Sum of the images after the registration*** | ***Difference of the images after the registration***

Registration **based on Iterative Optimization**

Example 5

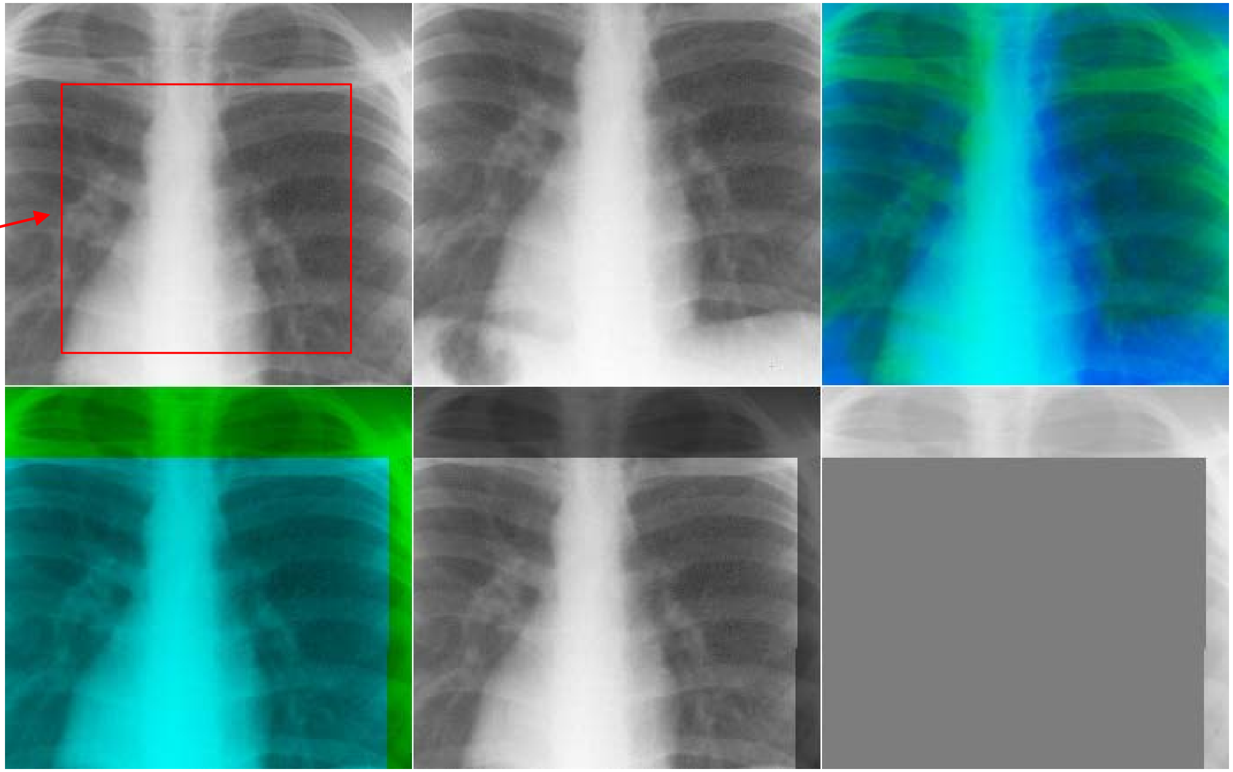
Registration: 2D, monomodal, intrasubject (without pre-registration)

Similarity measure: MSE computed only in the ROI defined

Processing time: 1.6 s - AMD Turion64, 2.0 GHz, 1.0 GB of RAM

Images dimensions: 230x216 pixels

Fixed image (X-ray) | ***Moving image (X-ray)*** | ***Overlapped images before the registration***

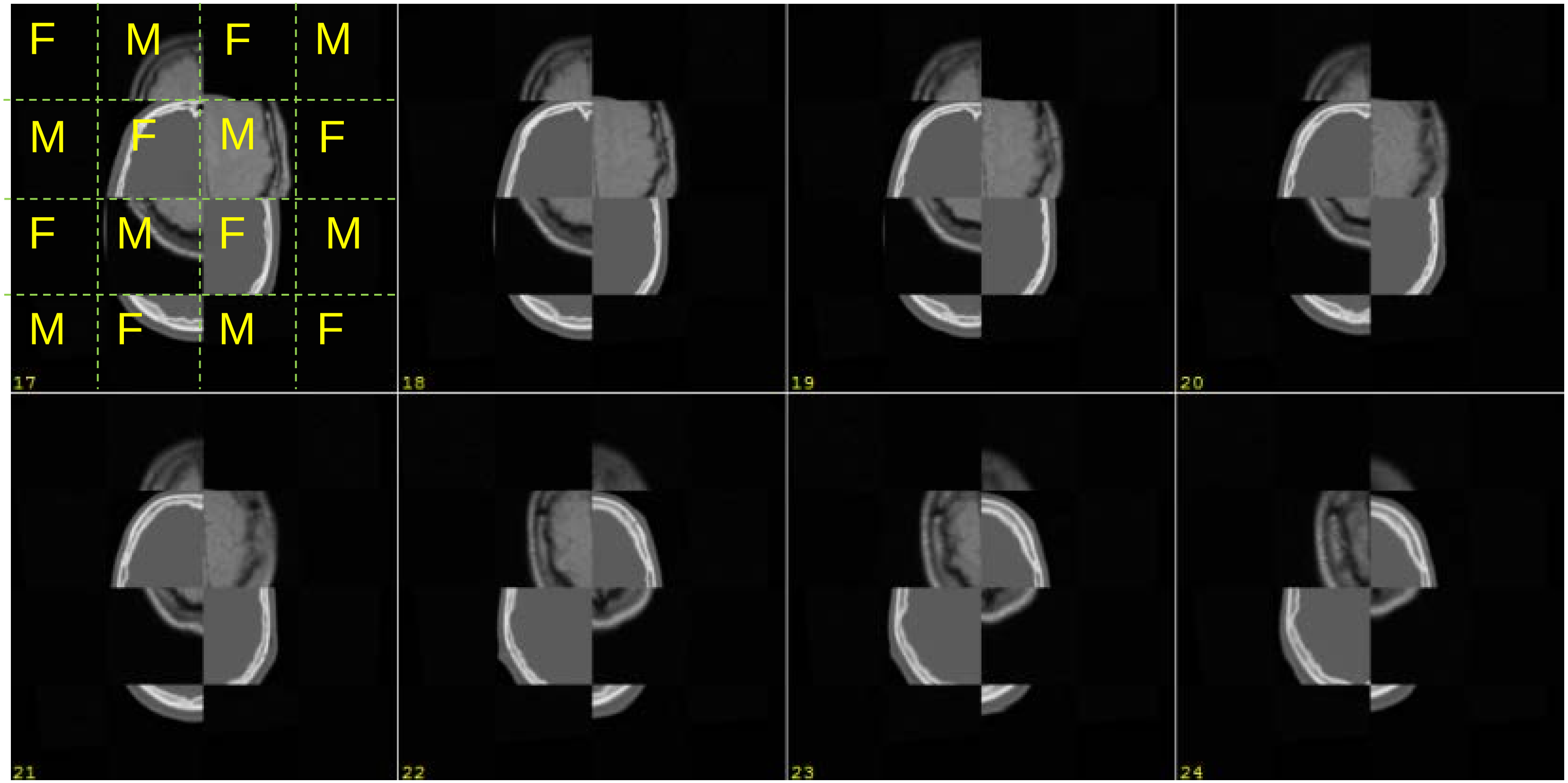


Overlapped images after the registration | ***Sum of the images after the registration*** | ***Difference of the images after the registration***

Registration **based on Iterative Optimization**

Example 6 – 3D

"Checkerboard" of the images before the registration (CT/MRI-PD, brain)

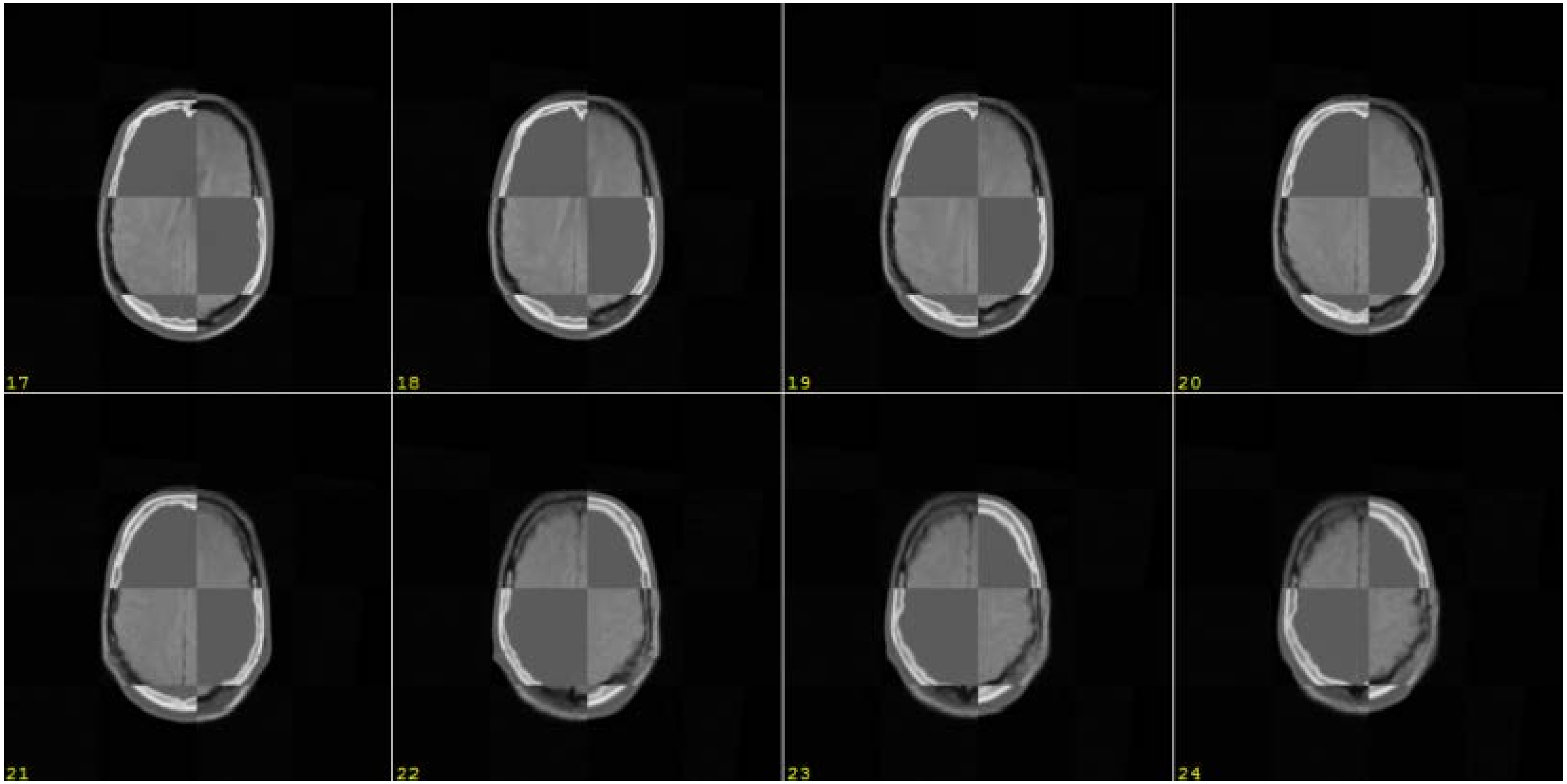


The "checkerboard" image is built by interchanging square patches of both images and preserving their original spatial position in the fixed (F) and moving (M) images

Registration **based on Iterative Optimization**

Example 6 – 3D

Checkerboard of the images after the registration (CT/MRI-PD, brain)

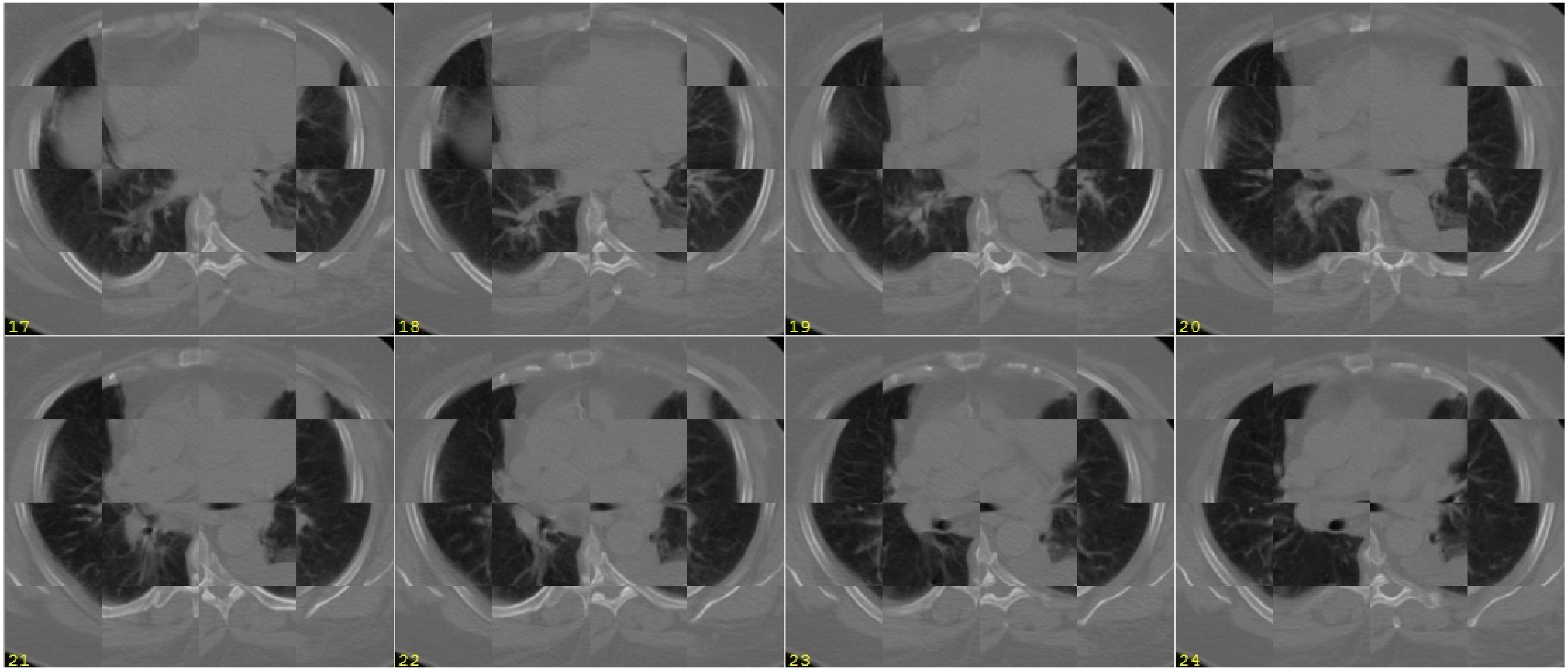


Registration: 3D, multimodal, intrasubject; Similarity measure: MI

Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 7 – 3D

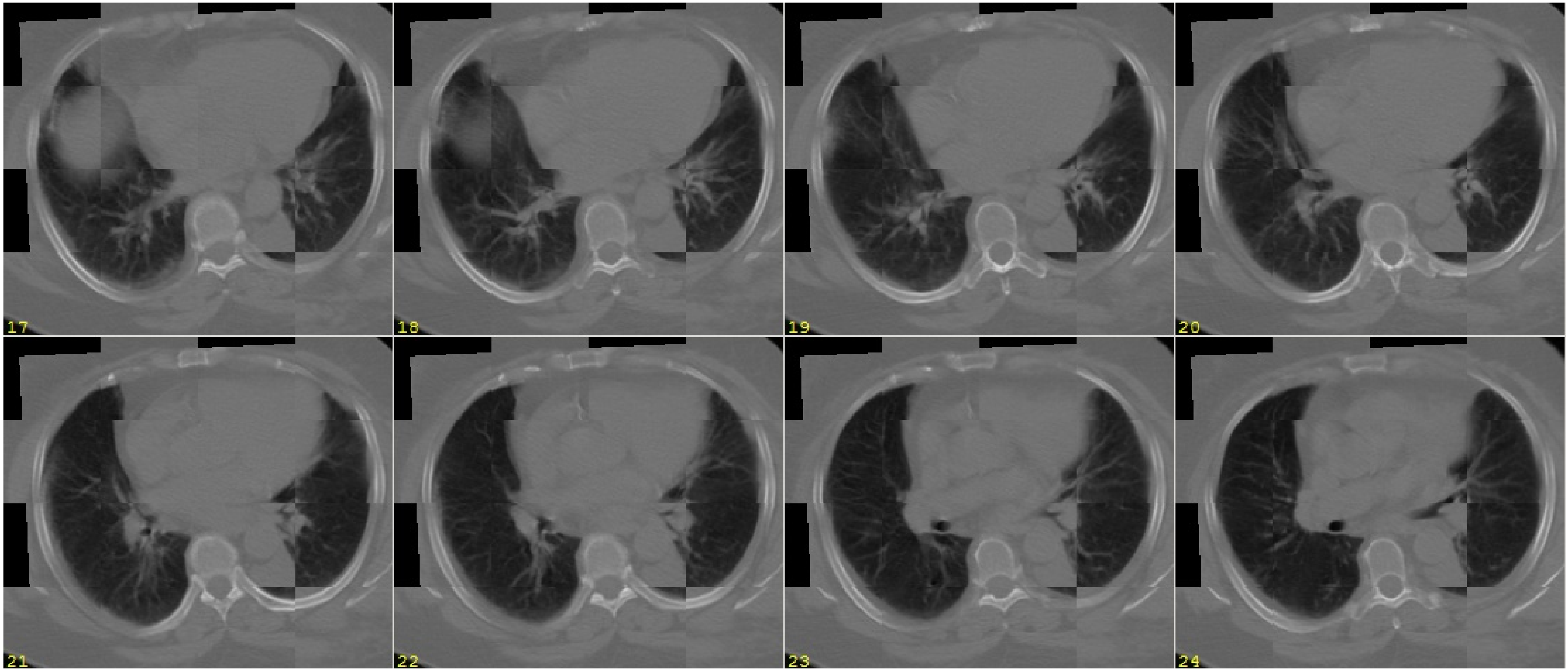
Checkerboard of the images (CT, thorax, Δt: 8.5 months) before the registration



Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 7 – 3D

Checkerboard of the images (CT, thorax, Δt: 8.5 months) after a rigid registration

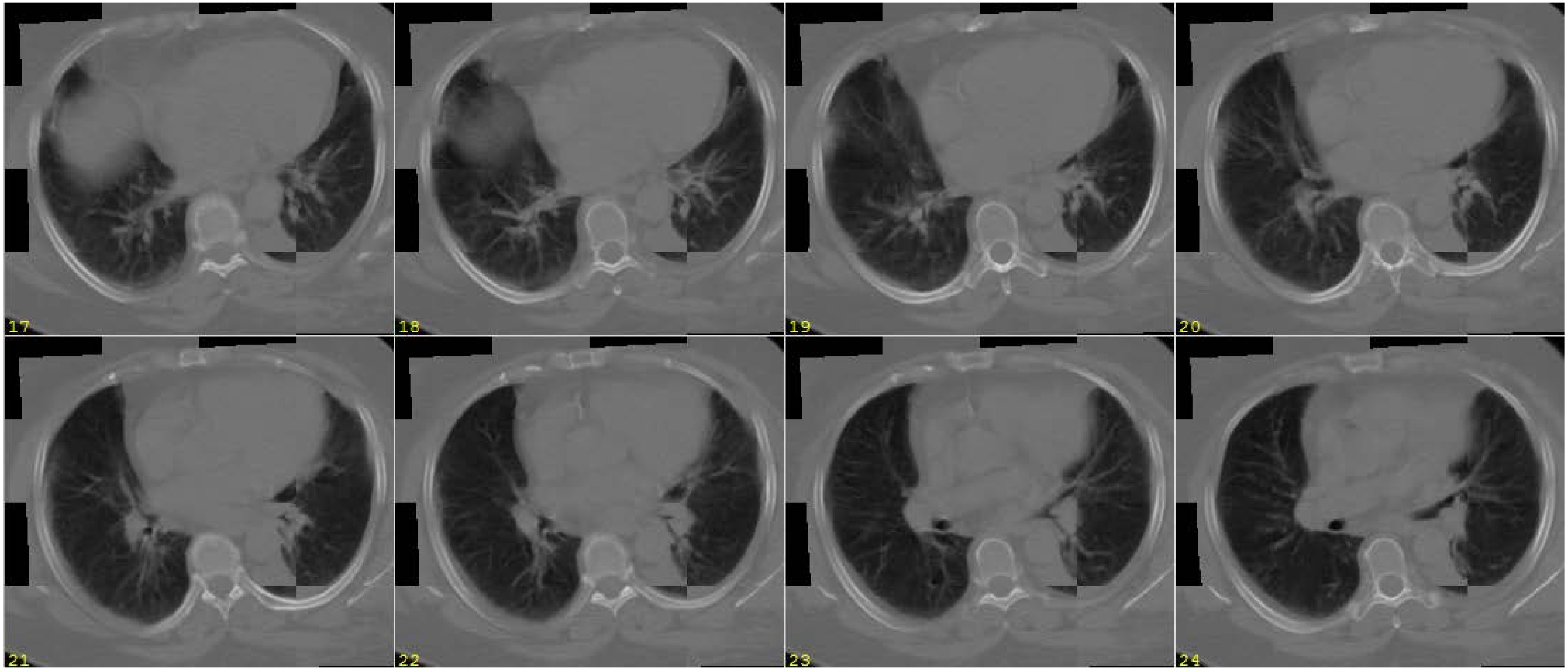


Registration: 3D, monomodal, intrasubject; Similatity measure: MI

Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 7 – 3D

Checkerboard of the images (CT, thorax, Δt: 8.5 months) after a cubic B-spline registration

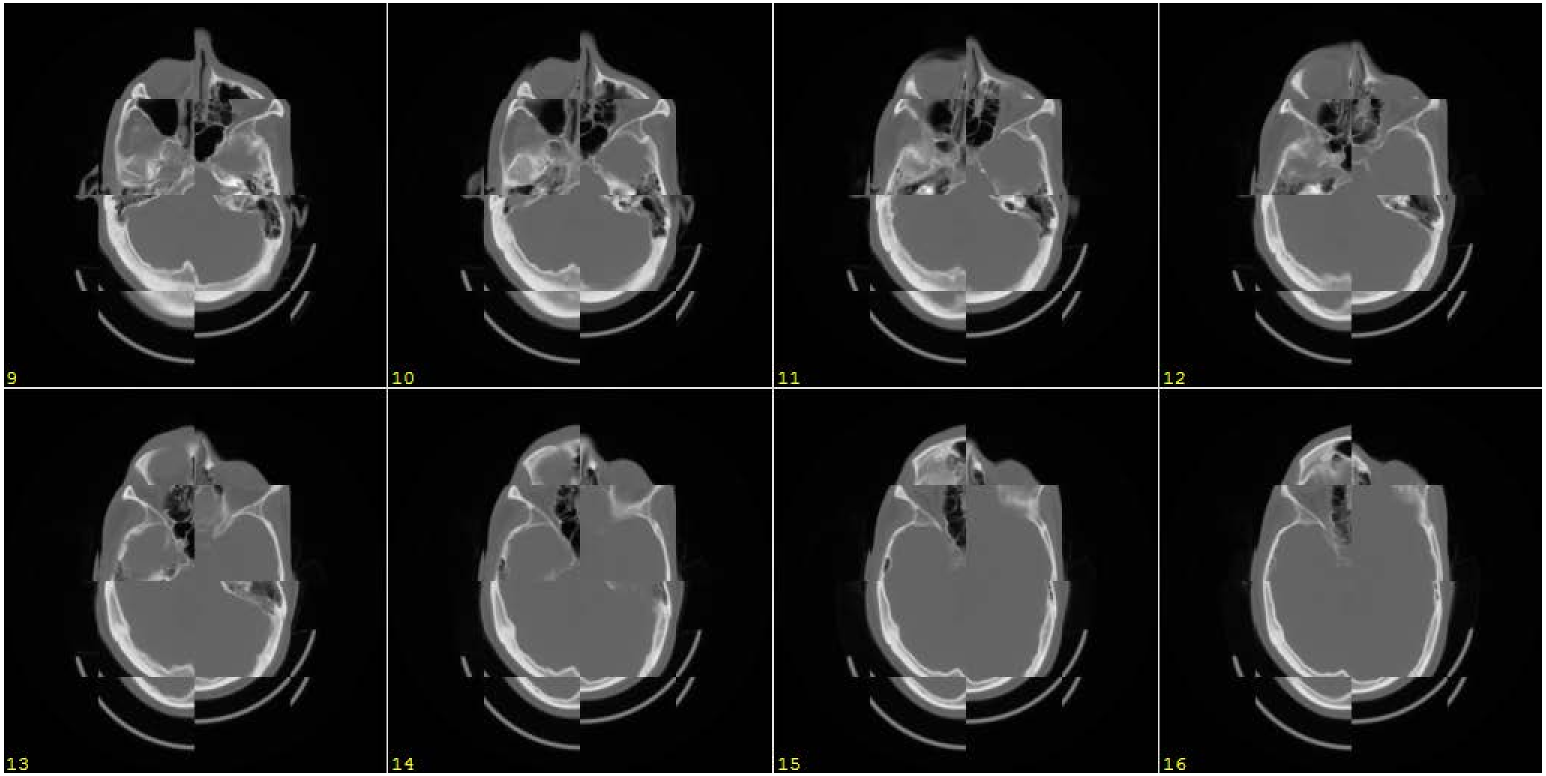


Registration: 3D, monomodal, intrasubject; Similatity measure: MI

Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 8 – 3D

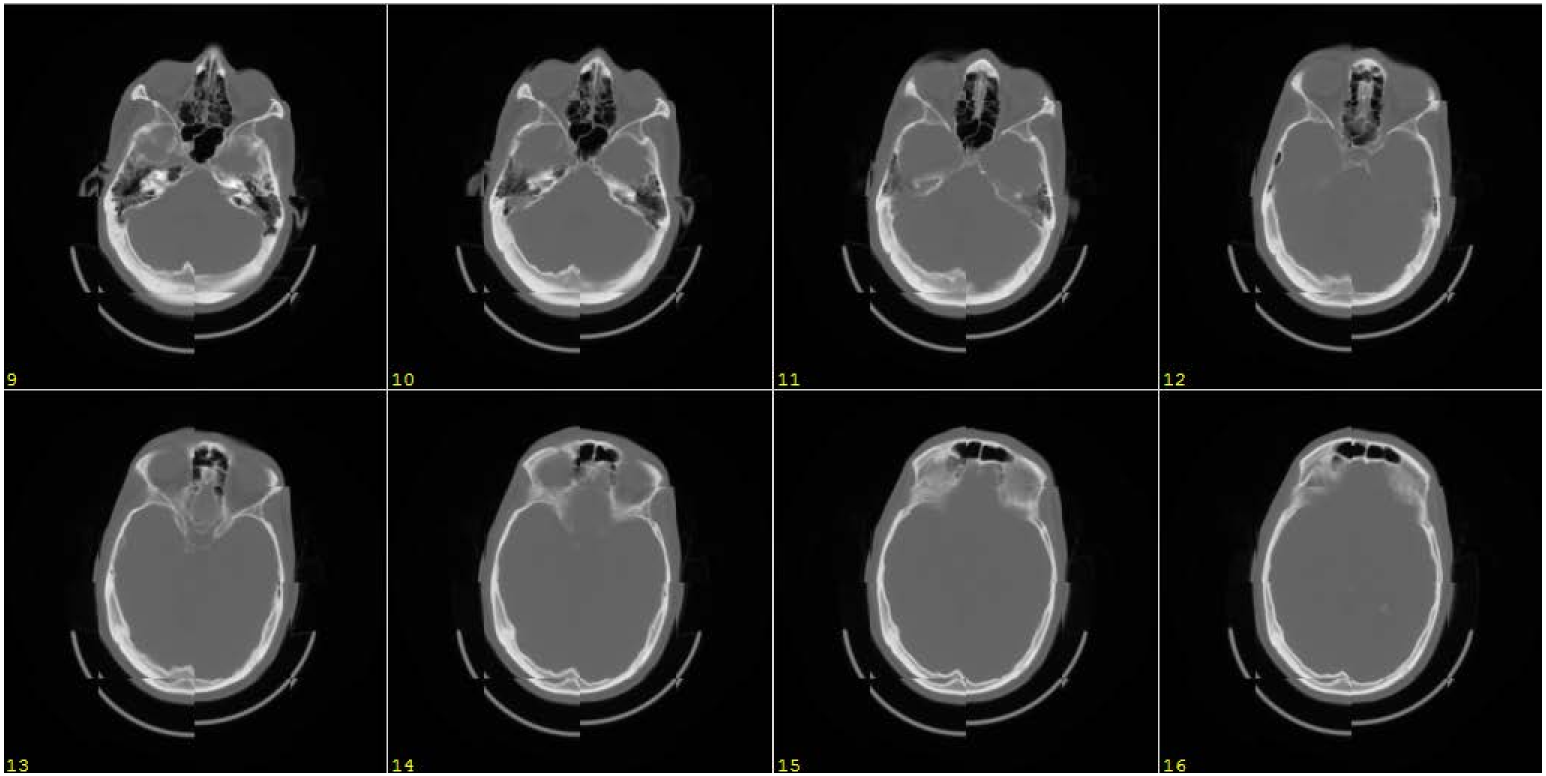
Checkerboard of the images (CT, brain) before the registration



Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 8 – 3D

Checkerboard of the images (CT, brain) after an affine registration

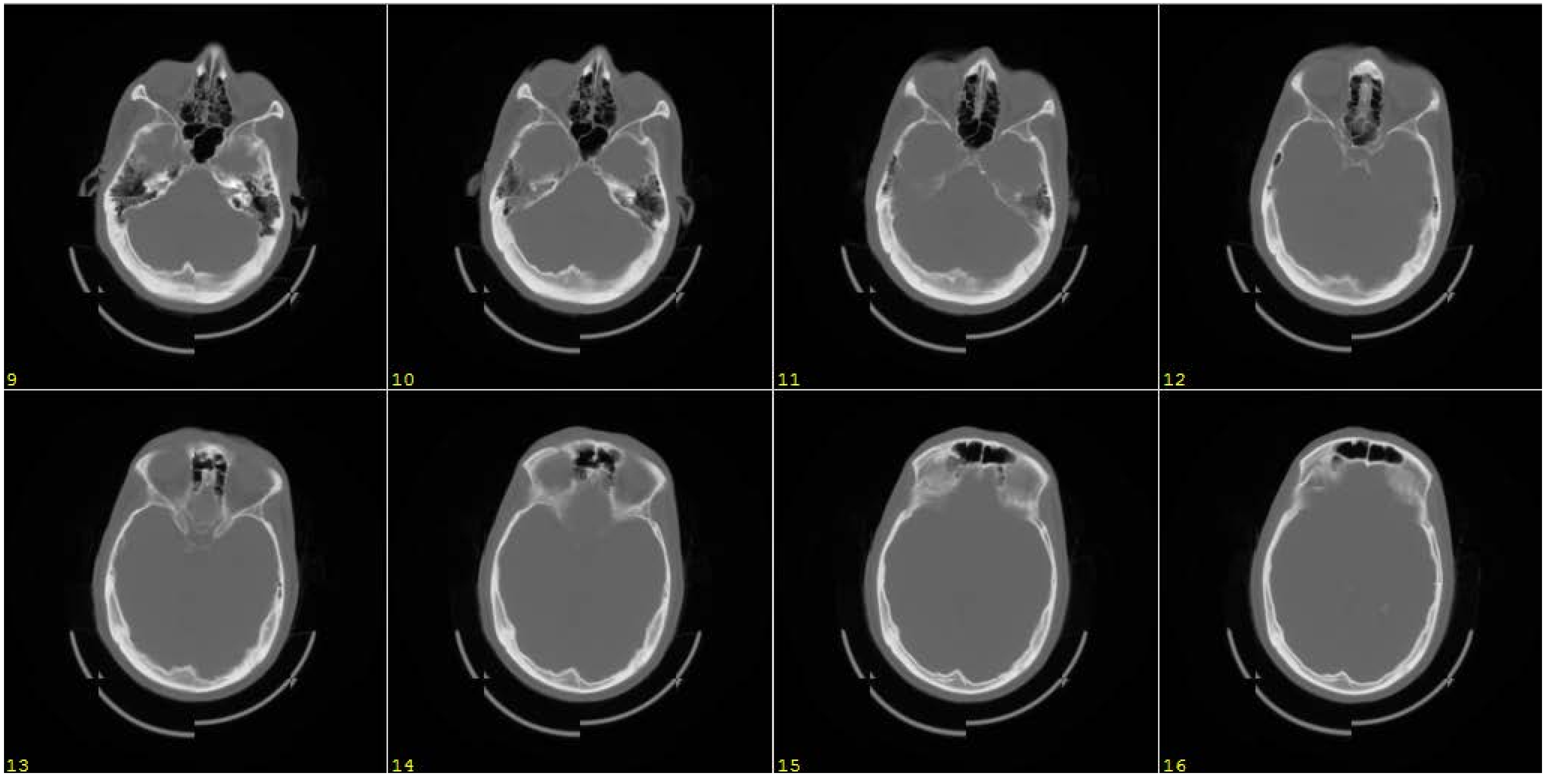


Registration: 3D, monomodal, intersubject; Similarity measure: MI

Registration **using Iterative Optimization and a curved transformation based on B-splines**

Example 8 – 3D

Checkerboard of the images (CT, brain) after a cubic B-spline registration

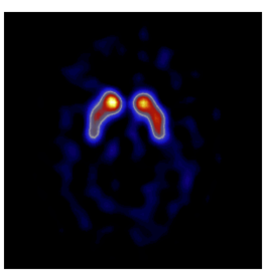


Registration: 3D, monomodal, intersubject; Similarity measure: MI

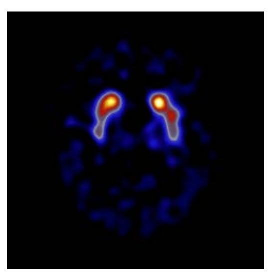
Applications in DaTSCAN SPECT image studies

DaTSCAN SPECT images are used to assist the diagnosis of the Parkinson’s disease and to distinguish it from other degenerative diseases. The solution developed is able to:

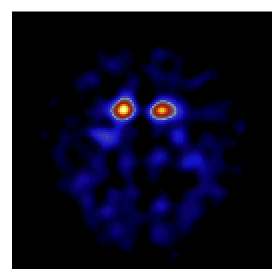
- Segment the relevant areas and perform dimensional analysis
- Quantify the binding potential of the basal ganglia
- Automatic computation of statistical data regarding a reference population
- Provide statistical analysis and comparisons relatively to the reference values of a population



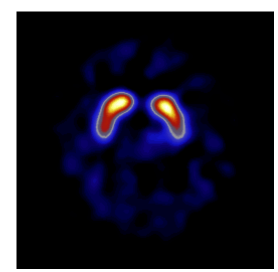
Normal



Alzheimer



Idiopathic Parkinsonism

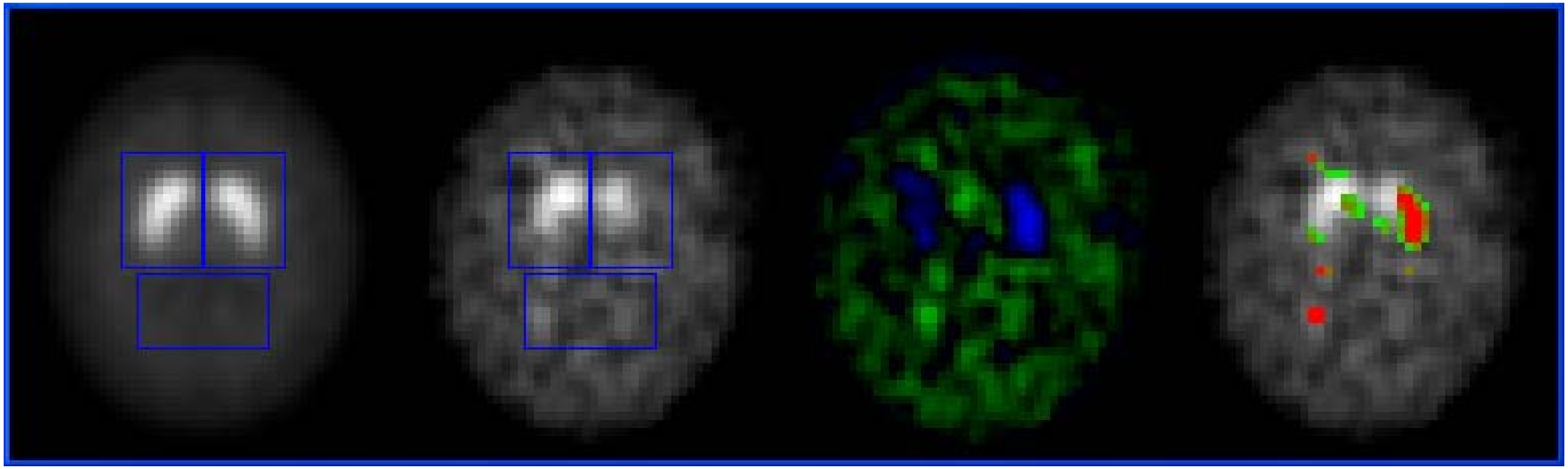


Essential tremor

Applications in DaTSCAN SPECT image studies

Example

The 3D volume images are automatically registered



Mean slice from the population used as reference

Corresponding slice of a patient

Difference of intensities

Z-scores mapping over the slice

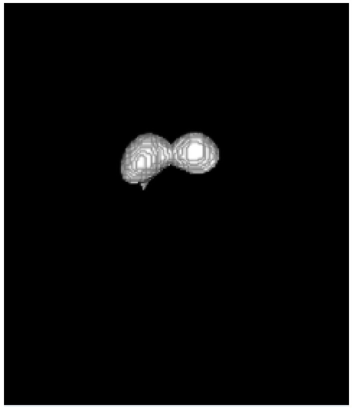
(The blue rectangles represent the 3D ROIs used to compute the binding potentials, which are based on the counts inside the ROIs. On the z-score mapping image, the red color means high z-score values)

Applications in DaTSCAN SPECT image studies

Example

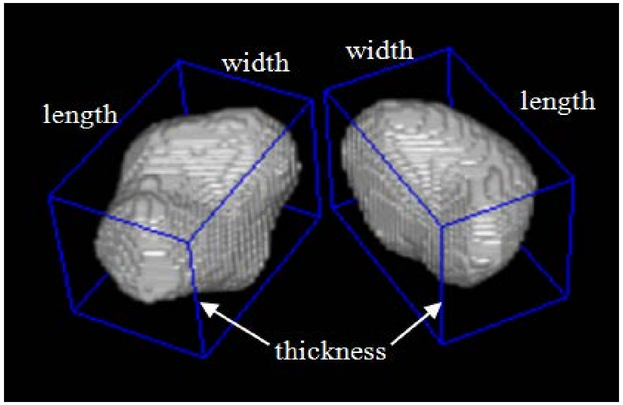
3D basal ganglia shape reconstruction and quantification

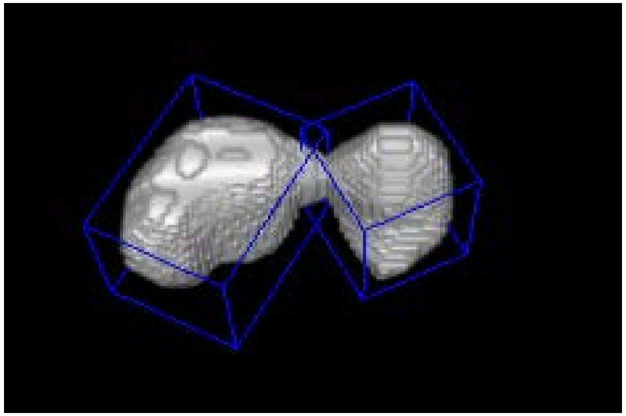
Basal ganglia from a mean image of a normal population



Basal ganglia from a patient with idiopathic Parkinson's disease

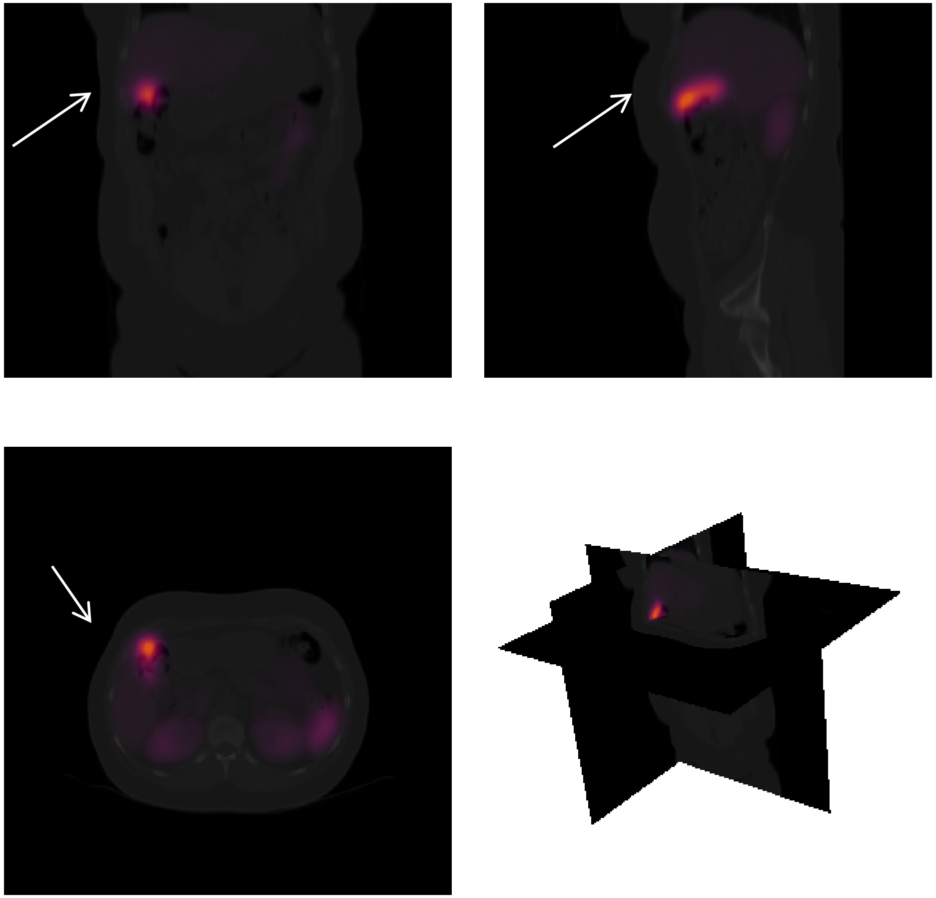
Basal ganglia from a patient with vascular Parkinson's disease



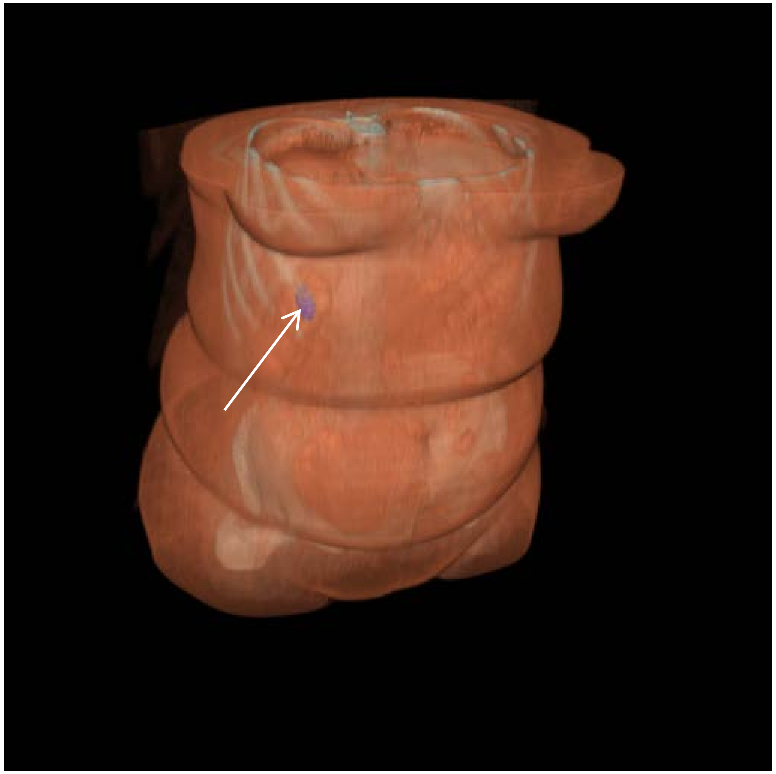


Applications in SPECT/CT registration and fusion

Example



Three slices (coronal, sagittal and axial) after registration and identification of the lesion



3D visualization after fusion CT/SPECT (the lesion identified in the SPECT images is indicated)

Conclusions

Conclusions

- **Hard efforts have been done by the Computational Vision community to develop methods more robust and efficient to register image data**
- The **Biomedical area has been one of the major promoters for such efforts**; particularly, due to the requirements in terms of low computational times, robustness and of complexity of the structures involved
- We have been developing several methods that have been applied successfully
- **However, several difficulties still to be overcome and better addressed**; such as, severe non-rigidity, complex spatio & temporal behaviors, high differences between the data to be registered (e.g. from very dissimilar image sources), etc.

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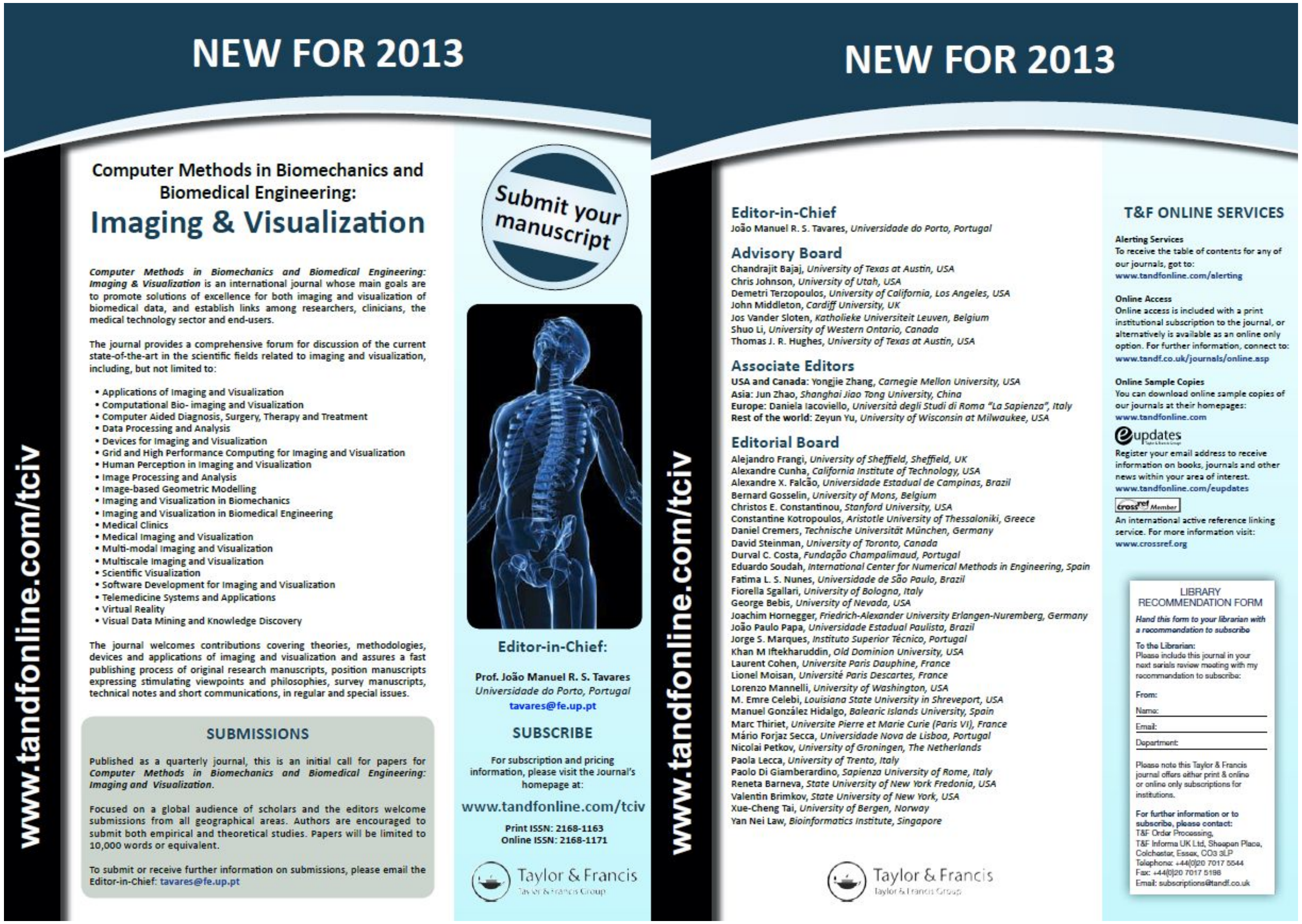

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