

Assessing Non-Rigid Registration Without Using Ground Truth

R. S. Schestowitz, V. Petrovic, C. J. Twining, T. F. Cootes, and C. J. Taylor

Abstract

We present a method for assessing the performance of non-rigid registration algorithms, without the need for any form of ground truth. The method exploits the fact that, given a set of non-rigidly registered images, a generative statistical appearance model can be constructed. The quality of the model depends on the quality of the registration, and can be evaluated by comparing images sampled from it with the original image set. We derive indices of model specificity and generalisation, and show that they demonstrate the loss of registration as a set of correctly registered images is progressively perturbed. We also show an application of the method to comparing the performance of three different registration algorithms.

1. Introduction

Over the past few years, non-rigid registration (NRR) has been used increasingly as a basis for medical image analysis. Applications include structural analysis, atlas matching and change analysis [4]. Many different approaches to NRR have been proposed, for registering both pairs and groups of images [3, 17]. These differ in terms of the objective function used to assess the degree of mis-registration, the representation of spatial deformation fields, and the approach to minimizing the mis-registration with respect to the deformations. The problem is highly under-constrained and, given a set of images to be registered, each approach will, in general, give a different result. This leads to a requirement for methods of assessing the quality of registration.

Various methods have been proposed for assessing the results of NRR [7, 9, 14, 13]. Most of these require access to some form of ground truth. One approach involves the construction of artificial test data, which limits application to 'off-line' evaluation. Other methods can be applied directly to real data, but require that anatomical ground truth be provided, typically involving annotation by an expert. This makes validation expensive and prone to subjective error.

In this paper we present a method for evaluating the results of NRR that relies on the image data alone, and can thus be applied routinely without the need for ground truth. It is based on the observation that, given a set of registered images, it is possible to construct a statistical model of appearance. If the registration is correct, this provides a concise description of the set of images. If it is incorrect, the performance of the model degrades. We base our assessment of the quality of registration on the quality of the resulting model.

In the remainder of the paper we explore the background, explain the method in detail, and present validation results using data for which the correct registration is known.

2. Background

2.1. Assessing Non-Rigid Registration

One approach to assessing the results of NRR is to create a set of test images by taking original images and applying known spatial deformations. Evaluation involves comparing the deformation fields recovered by NRR to those known to have been applied [13, 14]. This approach can be used to test a given NRR method 'off-line', but cannot be used to evaluate the results when the method is applied to real data as part of a registration-based analysis.

An alternative approach involves measuring the coincidence of anatomical annotations following registration. Variants of this approach include measuring the mis-registration of anatomical landmarks [7, 9], and the overlap between anatomically equivalent regions obtained using manual or semi-automatic segmentation [9, 13]. These methods are of general application, but are labour-intensive and error prone.

2.2. Statistical Models of Appearance

Statistical models of shape and appearance (combined appearance models) were introduced by Cootes, Edwards, Lanitis and Taylor [1, 2, 6], and have since been applied extensively in medical image analysis [8, 11, 15]. The construction of an appearance model depends on establishing a dense correspondence across a training set of images using a set of landmark points marked consistently on each training image.

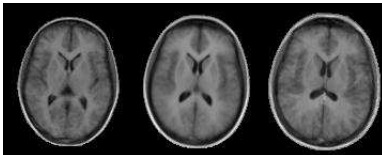


Fig. 1. The effect of varying the first model parameter of a brain appearance model by ± 2.5 standard deviations.

Using the notation of Cootes [2], the shape (configuration of landmark points) can be represented as a vector \mathbf{x} and the texture (intensity values) represented as a vector \mathbf{g} .

The shape and texture are controlled by statistical models of the form

$$\begin{aligned}\mathbf{x} &= \bar{\mathbf{x}} + \mathbf{P}_s \mathbf{b}_s \\ \mathbf{g} &= \bar{\mathbf{g}} + \mathbf{P}_g \mathbf{b}_g\end{aligned}\tag{1}$$

Where \mathbf{b}_s are shape parameters, \mathbf{b}_g are texture parameters, $\bar{\mathbf{x}}$ and $\bar{\mathbf{g}}$ are the mean shape and texture, and \mathbf{P}_s and \mathbf{P}_g are the principal modes of shape and texture variation respectively.

Since shape and texture are often correlated, we can take this into account in a combined statistical model of the form

$$\begin{aligned}\mathbf{x} &= \bar{\mathbf{x}} + \mathbf{Q}_s \mathbf{c} \\ \mathbf{g} &= \bar{\mathbf{g}} + \mathbf{Q}_g \mathbf{c}\end{aligned}\tag{2}$$

where the model parameters \mathbf{c} control the shape and texture simultaneously and \mathbf{Q}_s , \mathbf{Q}_g are matrices describing the modes of variation derived from the training

set. The effect of varying one element of \mathbf{c} for a model built from a set of 2D MR brain image is shown in Fig. 1.

3. Model-Based Evaluation

3.1. Specificity and Generalisation

Our approach to the assessment of NRR relies on the close relationship between registration and statistical model building, and extends the work of Davies et al. on evaluating shape models [5]. We note that NRR of a set of images establishes the dense correspondence which is required to build a combined appearance model. Given the correct correspondence, the model provides a concise description of the training set. As the correspondence is degraded, the model also degrades in terms of its ability to reconstruct images of the same class, not in the training set (Generalisation), and its ability to only synthesise new images similar to those in the training set (Specificity). If we represent training images and those synthesised by the model as points in a high dimensional space, the clouds represented by training and synthetic images ideally overlap fully (see Fig. 2). Given a measure of the distance between images (see next section), Specificity, S , Generalisation, G , and their standard errors σ_S and σ_G can be defined as follows:

$$G = \frac{1}{n} \sum_{i=1}^n \min_j |I_i - I_j|, \quad (3)$$

$$S = \frac{1}{m} \sum_{j=1}^m \min_i |I_i - I_j|. \quad (4)$$

$$\sigma_G = \frac{SD(\min_j |I_i - I_j|)}{\sqrt{n-1}}, \quad (5)$$

$$\sigma_S = \frac{SD(\min_j |I_i - I_j|)}{\sqrt{m-1}}. \quad (6)$$

where $\{I_j : j = 1..m\}$ is a large set of images sampled from the model, $|\cdot|$ is the distance between two images and SD is standard deviation.

Both values are low for a good model. Specificity measures the mean distance between images generated by the model and their closest neighbours in the training set, whilst Generalisation measures the mean distance between images in the training set and their closest neighbours in the synthesised set. The approach is illustrated diagrammatically in Fig. 3.

3.2. Measuring Distances in Between Images

The most straightforward way to measure the distance between images is to treat each image as a vector formed by concatenating the pixel/voxel intensity values, then take the Euclidean distance. Although this has the merit of simplicity, it does not provide a very well-behaved distance measure since it increases rapidly for quite small image misalignments. This observation led us to consider an alternative distance measure, based on the 'shuffle difference', inspired by the 'shuffle transform' [10]. The idea is illustrated in Fig. 4. Instead of taking the sum of squared differences between corresponding pixels, the minimum absolute difference between each pixel in one image and the values in a shuffle neighbourhood around

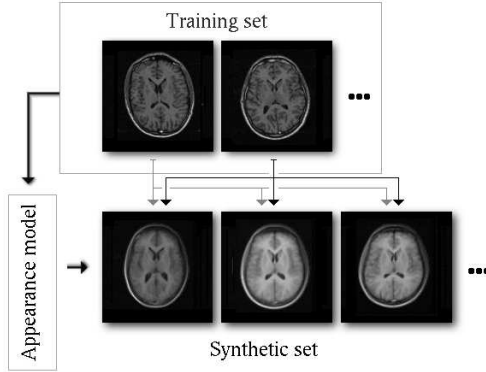


Fig. 3. The model evaluation framework. Each image in the training set is compared against every image generated by the model

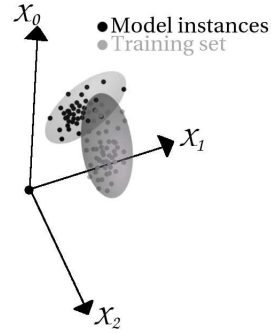


Fig. 2. Training set and model synthesis in hyperspace

the corresponding pixel is used. This is less sensitive to small misalignments, and provides a more well-behaved distance measure.

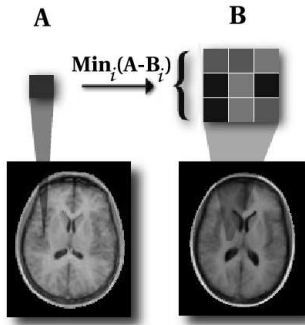


Fig. 4. The calculation of a shuffle difference image

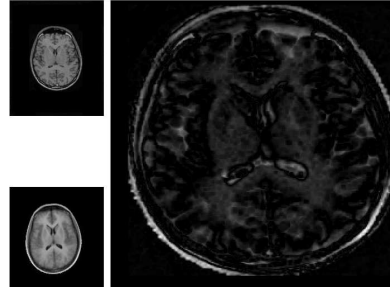


Fig. 5. An example of the shuffle difference image (right) when applied to two MR slices (left)

4. Validation of the Approach

4.1. Perturbing Ground-Truth

We conducted a series of experiments to test the hypothesis that reduced registration accuracy can be detected using model specificity and generalisation. An equivalent 2D mid-brain T1-weighted slice was obtained from each of 36 subjects using a 3D acquisition. A fixed number (167) of landmark points were positioned manually on the cortical surface, ventricles, caudate nucleus and lentiform nucleus, and used to establish a ground-truth dense correspondence over the set of images, using locally affine interpolation. A statistical appearance model was constructed using the methods described in 2.2, with the set of landmark coordinates forming the shape vector \mathbf{x} for each image. Keeping the shape vectors fixed, we then applied a series of smooth pseudo-random spatial warps to the training images, resulting in successively increasing mis-registration. Each warp resulted in an average point displacement of between one and two pixels. Specificity and

Generalisation results were obtained for 0, 1, 5, and 10 warps per image, using $m = 1000$.

4.2. Effects of the Shuffle Transform

The experiment described in the previous section was repeated for shuffle neighbourhoods of 1x1 (Euclidean distance), 3x3, 5x5, and 7x7, to test the hypothesis that this would extend the range over which different degrees of mis-registration could be discriminated.

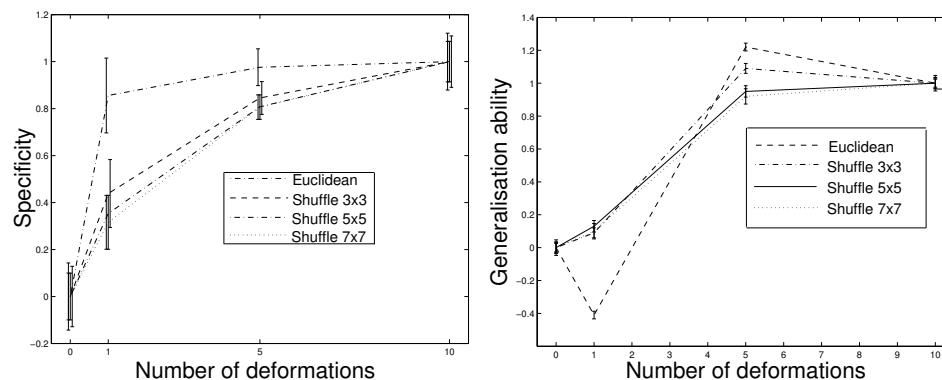


Fig. 6. Specificity and Generalisation for increasing mis-registration of different shuffle neighbourhood sizes.

4.3. Comparing Different Methods of NRR

A common task in medical image analysis is the estimation of correspondences across a group of images, to allow mapping of effects into a common co-ordinate frame when performing population studies. A widely used approach is to use a non-rigid registration algorithm to map a chosen reference image onto each example, defining the correspondence across the group [11]. However, it has been argued [3] that this *pairwise* approach does not take advantage of the full information in the group, and thus may lead to sub-optimal registration. We have been investigating *groupwise* methods of registration which aim to make the best use of the group as a whole when estimating the correspondence. We work within a minimum description length (MDL) framework. The aim is to construct a statistical appearance model which can exactly synthesize each example in the training set as efficiently as possible [16]. It has been observed that the more the compact the representation, the better the correspondences. The general approach is to define a deformation field between reference frame and each training image. For a given choice of sets of fields, one can compute the cost of encoding the images (a combination of the coding cost of the model, the cost of the parameters and the cost of residuals between the synthesized images and the training images). The effect on this total description length of modifying the deformation fields can be evaluated - the correspondence problem becomes a (very high dimensional) optimisation problem. Within this general framework we compare three different approaches (for details see [16]):

1. Pairwise registration, using the first image as a reference
2. Groupwise registration in which the reference model is just the current mean of the shape and intensities across the training set, and no constraints are placed on the deformations
3. Groupwise registration to the mean including a term encouraging a compact representation of the set of deformations

Though the algorithms will work in 3D, for the evaluation experiments we concentrate on a 2D implementation (allowing more large-scale experiments to be performed). We have a dataset of 104 3D MR images of normal brains¹, which have been affine aligned and a single slice at equivalent location extracted from each. Fig. 5 (left) shows examples of extracted slices. In order to evaluate the different registration algorithms outlined above, we register the 104 2D slices using the different techniques, construct statistical models from them and calculate the specificity and generalisation measures.

5. Results

The results of the experiment to test the effect of increasing mis-registration are shown in Fig. 6. These demonstrate that, for all sizes of shuffle neighbourhood, the specificity and generalisation values increase (get worse) with increasing mis-registration². The results for different sizes of shuffle neighbourhood demonstrate that the range of mis-registration over which distinct values of specificity and generalisation are obtained increases as the neighbourhood size increases.

The results of the comparison between three different methods of NRR are shown in Fig. 9. These show that, particularly in terms of specificity, we can distinguish between the three approaches, with the fully groupwise method performing best, as anticipated. A model built using this approach is shown in Fig. 8.

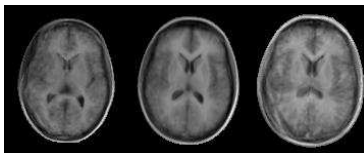


Fig. 7. The first mode of an appearance model of the brain whose training set was subjected to deformation. ± 2.5 standard deviations are shown.

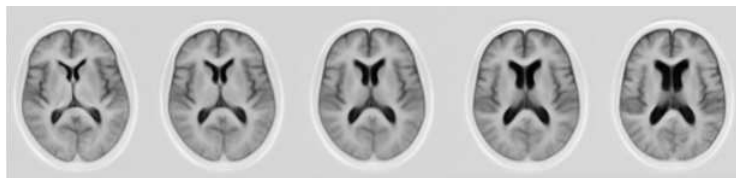


Fig. 8. Appearance model which was built automatically by group-wise registration. First mode is shown, ± 2.5 standard deviations.

¹ The age matched normals in a dementia study generously provided by X (*anonymised*).

² Except that Generalisation is unstable for a 1x1 shuffle neighbourhood (Euclidean distance).

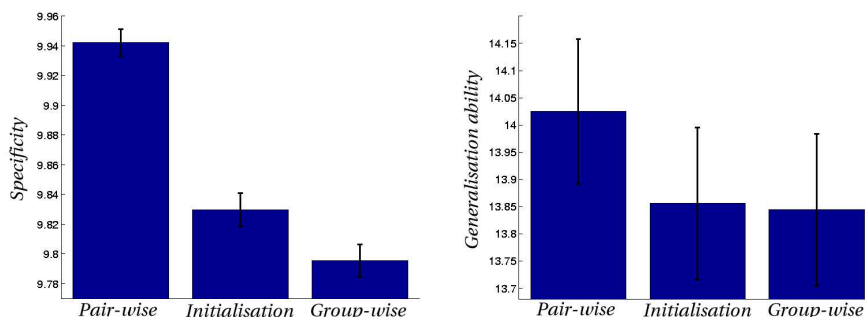


Fig. 9. Registration evaluation which compares 3 different registration algorithms. Specificity is shown on the left and generalisation ability on the right. Values are the mean over a wide range of modes in the model.

6. Discussion and Conclusions

We have introduced a model-based approach to assessing the accuracy of non-rigid registration, without the need for ground truth. The validation experiments, based on perturbing correspondences obtained using ground truth, show that we are able to detect increasing mis-registration using just the registered image data. The results obtained for different sizes of shuffle neighbourhood show that the use of shuffle distance rather than Euclidean distance improves the range of mis-registration over which we can detect significant changes in registration accuracy. We have also shown that the approach is capable of detecting statistically significant differences in registration accuracy between three different (plausible) approaches to NRR.

We believe that this represents an important advance in the assessment of NRR, because it establishes an entirely objective basis for evaluating the reliability of NRR-based experiments, and for comparing the performance of different methods of NRR. The fact that no ground truth data is required means that the method can be applied routinely. Further work is needed to compare the results obtained using our new approach with those obtained using more sophisticated segmentation-based methods of evaluation.

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