Registration of The Vertebrae

Wei Li, Lixu Gu*, Jianrong Xu* and Kan Cheng

***Abstract*— The vertebrae registration is very important to treat the vertebrae diseases. As the vertebrae has rigid bones and soft tissue, the traditional nonrigid registration can't work well on that. In this paper, a novel multi-stage nonrigid registration with rigid constraint to the vertebrae is presented. Firstly, A new rigid transform constraint is introduced, which penalizes nonrigid deformations at locations where it is required. The nonrigid registration method based on B-Spline is extended to allow the incorporation of the rigid transformation. Secondly, the vertebrae registration using the vertebrae property and the nonrigid registration with rigid constraint is introduced. Thirdly the registration experiments are performed on 2D synthetic data and the vertebrae slices. Experiments show that the proposed registration with rigid constraint is successful to improve the vertebrae registration quality.**

I. INTRODUCTION

Nonrigid registration [1] [2], which is widely used in the field of medical imaging, usually models all the tissue as nonrigid objects and does not take rigidity of different tissue types into account. As is known that the vertebrae has several vertebra bones. If the vertebrae are registered, these nonrigid registration algorithms will not necessarily preserve the rigidity of these bones. These bones are required to keep rigid when they are registered.

Preservation of the rigidity is not only useful for the bones that is rigid by nature but also very useful in many cases. If we register the two images that have the structures changed in size, it will be useful to retain the difference of the structures such as tumor growth between follow-up images. Traditional nonrigid registration matches two images to the same size, and no difference will be observed. Tumor growth will be concealed. Keeping the tumor objects rigid can prevent this.

Several methods to constrain deformations for the nonrigid registration have discussed in the literature. The most common approach is to employ a regularization or penalty term, that is to say, employ a modified metric. This method is evolved from the smoothness constraint which was proposed by D.Rueckert.[1] Torsten Rohlfing [3] proposed a global Jacobian constraint. Dirk Loeckx [4] extended D.Rueckert's constraint to the required regions. After that, Marius Staring etc [5] proposed a composite constraint which includes linearity constraint, orthonormality constraint and properness constraint. Particular methods to constrain the transformation have also been proposed. Little et al. [6] incorporate independent rigid objects in a modified thin-plate spline nonrigid registration. Tanner et al. [7] proposed a solution that locally couples the control points of a B-spline FFD field such as to make the transformation rigid within the specified image region of interest. Kexiang Wang[8] proposed a method which incorporates rigid structures in non-rigid registration using triangular B-Splines and he employed this method to the registration of the human spines.

The purpose of this paper is to present a new, easy understood but efficient method to register the vertebrae. At first, a new rigid constraint transform based on B-Spline is presented, which couples the rigid control points together. All of these control points move together and keep the correspondence position, that can keep the tissue within these control points rigid. Then, a multi-stage vertebrae registration is introduced. The property of the vertebrae is used to get the initial parameters of these control points, then nonrigid registration with rigid constraint transform is used to get the last registration result.

This paper is organized as follow: in Section 2, the algorithm to constrain the transform and the vertebrae registration are presented. In Section 3, experiments to show the features of this rigid constraint transform and the vertebrae registration algorithm will be presented. Conclusions and discussions are given in Section 4.

II. METHODS

Our nonrigid registration with rigid constraint framework is based on the B-Spline Registration. Metric is NMI [9], and the optimization is regular gradient decent algorithm. The transform is based on B-Spline that is modified using a rigid constraint which will be discussed as below:

A. Rigid Constraint Transform

Normally, transformation is divided into two types: rigid transform $T_R(x)$ (translation, rotation, scale, affine etc) and nonrigid transform $T_N(x)$(B-Spline, TPS [10]etc).

So we can get a hybrid transform $T(x)$ as the following formulation:

$$Tx = \alpha T_R(x) + (1 - \alpha) T_N(x) \tag{1}$$

Where $\alpha(0.0 \leqslant \alpha \leqslant 1.0)$ weighs rigidity coefficient. The coefficient is 1.0 on the pure rigid structure and 0.0 on the nonrigid tissue. The other parts will be in the middle of 0.0 and 1.0.

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The most popular nonrigid registration transform is FFD (Free-form Deformation)[1] based on cubic B-Spline. FFD formulation can be presented as:

$$u(x,y,z) = \sum_{l=0}^{3}\sum_{m=0}^{3}\sum_{n=0}^{3}\beta_l(u)\beta_m(v)\beta_n(w)\phi_{i+l,j+m,k+n} \tag{2}$$

Where β is the ith basic function of the B-Spline. ϕ_{ijk} is the B-Spline coefficients, it is also the control points. From the formulation, we know that only the near 4*4(2D) or 4*4*4(3D) pixels in the local neighborhood of that control points will change when that control points are changed. This is the the basic property of the cubic B-Spline. At the same time, if the near 4*4 or 4*4*4 control points perform the rigid transformation, all the pixels which are influenced by all the rigid control points will keep rigid.

The required or interesting region will be segmented firstly. The minimal 4*4 or 4*4*4 bounded closure control points can be got from the pre-segmented region. If all the closure control points perform rigid transformation, the required region will also keep rigid.

There exists a problem if 4*4 control points are extended. Some regions that are nonrigid parts will be turned into rigid parts. If the perimeter of the rigid parts is p and the rigid width is d. The extra extended region S_{extra} is about the following formulation below:

$$S_{extra} = \frac{pd}{2} \tag{3}$$

From the formulation, if the control points' width is too great, the extended rigid parts will be too much. On the other hand, if the width is small, the computation is too much. So, non-uniform B-spline is chosen to balance the magnified region and the computation. If n is the non-uniform step, then the extra extended region will be changed into the formulation below.

$$S_{extra} = \frac{pd}{2^{n+1}} \tag{4}$$

From the formulation above, if n is large enough, the extra extended rigid region will be the minimal.

In nature, the transformation of the rigid parts also can influence the neighbor nonrigid parts. The rigid transform weight can also be added to the neighbor nonrigid parts. In this system, the weight is in proportion to the pixels' distance to rigid parts. To simplify the computation, only the control points in the regions whose weight are not zero are chosen to add the weight and other pixels will be influenced by the control points.

Let φ_{rigid} be the set of rigid control points and φ_{weight} be the set of blend control points which have rigid and local transformation weight. The registration's transformation can be described as follow:

1) Get the pre-segmentation result of the rigid parts and use the minimal spacing's level control points to include the adjacent two control points in each direction to get the minimal rigid bounding box.
2) Use the minimal rigid bounding box to detect the upper control points to get the correct non-uniform division.
3) Perform rigid transformation to the set of control points ϕ_{rigid} and set the displacement to ϕ_{rigid}.
4) The set of blend control points' displacements are got from equation (1) and the rigid transformation $T_R(x)$ is got from the rigid control points nearby.
5) the B-Spline equation is used to get the last transformation result.

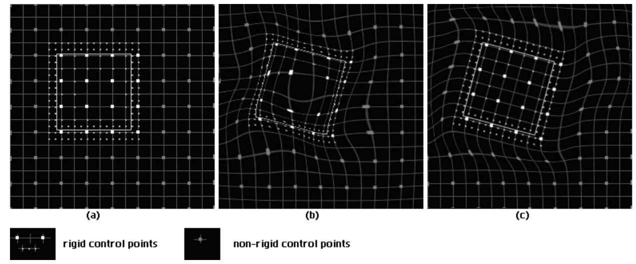

Fig. 1. 2D example of rigid transformation constraint using non-uniform B-spline. The rigid box's rotation is 15° and the FFD is based on a control spacing of 16 pixels. (a) the control points' non-uniform division. (b) transform the image using standard FFD. (c) transform the image using rigid transformation constraint.

This rigid constraint allows a coupled translation. That should be a sufficient approximation for the local transformation of a rigid object. Fig. 1 shows an example of rigid constraint transformation using non-uniform B-Spline.

B. The Vertebrae Registration

The vertebrae is composed of the vertebra bones and the soft tissues. If the registration is performed on the vertebrae, the bones will be transformed rigidly and the soft tissues will move freely. The nonrigid registration with rigid constraint can be used on the vertebrae. As we known the vertebrae bones are connected and move together. So, the property of the vertebrae can be used to improve the registration quality.

Our registration method can be described as below:

1) In the pre-process, every bone parts can be segmented firstly, the non-uniform division can be processed on these bones.
2) Get every part's center and use these centers to simulate a two order or three order splines. The nonrigid parts near the bone part will has the initial parameters which are got from the center splines.
3) Each part bone in the fixed image has it's correspondence bone in the moving image. The rigid registration is performed on each bone. This registration result can give us an initial parameters of each bone. This bone parameters and the soft tissues' initial parameters near the bones are the result of our first stage registration.
4) Use the nonrigid registration with rigid constraint which are described as above to perform our registration to get the last result.

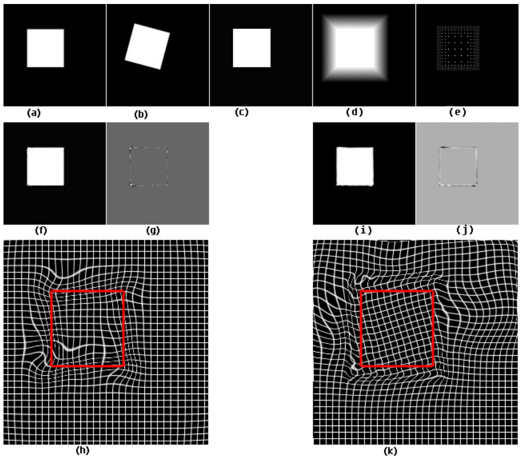

Fig. 2. The comparison of the registration with and without rigid transform constraint for 2D synthetic example. The white square in the images represent rigid structures. The black parts are the nonrigid parts. (a) fixed image. (b) moving image. (c) the pre-segmentation rigid image. (d) the weight image based on the pre-segmentation rigid image. (e) the non-uniform rigid control points which are generated from the pre-segmentation rigid image. (f) the output image of the nonrigid registration. (g) the different image of the nonrigid registration result and fixed image. (h) the transformation grid and the part within the red line is the rigid part. (i) the result image of the constraint registration. (j) the different image of the constraint registration result and the fixed image. (k) the constraint transformation gird and the part within the red line is the rigid part.

As we know, the bone part are connected and a curve constraint can be considered to add to the registration Metric.

In the first stage of the registration, the curve of bone center simulate to the two order or three order curve. If we find the best transform result, the distance between the center and the curves will be zero. So the curve constraint can be described as below:

$$E_{curve} = \sum_{i=1}^{n} (x_i - F_{curve}(y_i))^2 \tag{5}$$

where $(x_i, y_i)(i = 1, 2, \ldots, n)$ is the transform result of the vertebra bone centers and $F_{curve}(y)$ is the curve which has the parameter y.

and the last metric result will be also described as :

$$E_{total} = E_{metric} + \alpha E_{curve} \tag{6}$$

where α is the constraint coefficient.

III. Experiments

The experiment is employed on Win-XP Professional operation system and is programmed under Visual Studio 2005. Hardware environment is: Intel P4 2.8G (Hyper thread support), 1024M memory. The experiments are employed by the standard B-Spline nonrigid registration with and without rigid constraint.

A. Experiment1: Synthetic example

This experiment is to show the feature of rigid transform constraint. Rotation of a rigid object is illustrated with the square in the Fig. 2, where the white square is the rigid part and the background black is the nonrigid soft tissue. The rigidity coefficient is set to 1.0 on the square and 0.0 elsewhere. The images have the dimensions of 128 by 128 pixels, and the B-Spline grid is chosen as 17×17.

Both the algorithms get the similar registration results for the matching of the images in Fig. 2. However, the underlying deformation field is highly nonlinear if no rigid transform constraint is used. If it is used, the deformation field is almost perfectly rigid at the rigid part.

TABLE I

THE COMPARISON OF THE SYNTHETIC EXAMPLE REGISTRATION RESULT IN THE SQUARED SUM OF INTENSITY DIFFERENCES(SSD), NORMALIZED CROSS CORRELATION(NCC) AND NORMALIZED MUTUAL INFORMATION(NMI).

	SSD	NCC	NMI	$\tilde{\omega}$
before registration	1690.776	0.8852	1.445	5.5277
nonrigid registration	8.113	0.9995	1.894	4.3800
constraint registration	17.544	0.9981	1.810	0.9043

The moving image is got from the fixed image by the rotation 15° and left translation 5 pixels. So the perfect position of every pixel is known, this correspondence relationship can be thought as the "golden" standard. The white square is what we focused on, so the statistics is made on the pixels which are in the square. From Table I, both of the registrations have the similar result. But from the "golden" standard, the mean difference ($\tilde{\omega}$) is less than 1 pixel, the registration with rigid constraint can be thought as successful. But the standard nonrigid registration does not take the rigidity account, the mean difference will be greater.

B. Experiment2: Cervical vertebrae registration

Two MRI images of cervical vertebrae are used in the third experiment, the first stage of the registration is seen in Fig. 3. The data has slices of size 128 by 256. The vertebrae has 7 disks, and every disk should keep rigid and other tissue can perform nonrigid transformation. the B-Spline grid 9×17 and the non-uniform level 3 are used in the algorithms. A manual segmentation is made to every disk firstly in Fig. 3c,e. The centers are got from the bones in Fig. 3d,f. Then after the segmentation, every correspondence disk can be registered using rigid registration in Fig. 3j.

After the first stage, the result can be seen in the Fig. 3c,d and e. After the last nonrigid registration with rigid constraint, the last result show in the Fig. 3f,g and h. From the Fig. 3, the first stage's has the similar result with the last result. That can show us that the multi-stage vertebrae registration can improve the registration quality clearly.

As is seen from Fig. 3f, 3g and 3h, the parts within the red lines are the vertebrae bones. Every bone part can keep rigid and matched successfully when the whole image performs the nonrigid registration. This experiments can not only show that the nonrigid registration with rigid constraint can keep rigid parts rigid and other parts nonrigid but also show that the multi-stage vertebrae registration is successful to improve the registration quality.

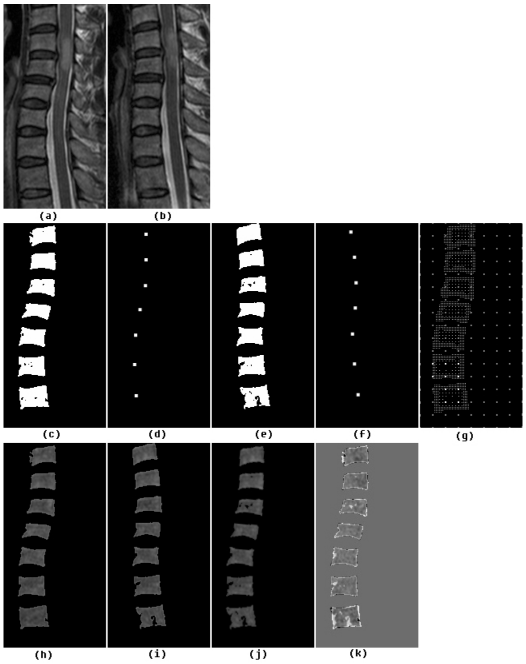

Fig. 3. the registration's first stage result of the 2D cervical vertebrae. (a) fixed image. (b) moving image. (c)(d) the fixed image's bones and centers. (e)(f) the moving image's bones and centers. (g) the non-uniform rigid control points. (h)(i) the bones of the fixed image and the moving image. (j) the bones of the moving image after the first stage. (k) the difference image of the bones.

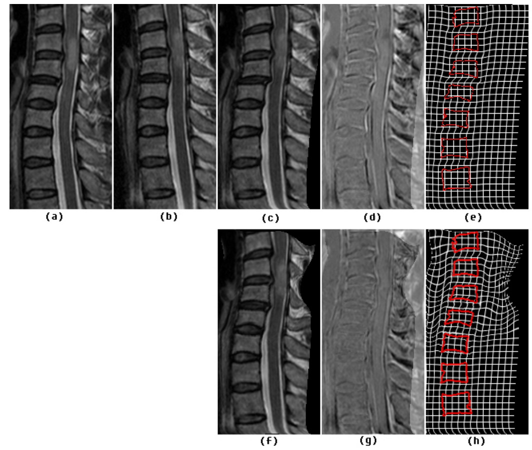

Fig. 4. the registration's first stage result of the 2D cervical vertebrae. (a) fixed image. (b) moving image. (c)(d)(e) the first stage result, difference image and the grid image of the registration. (f)(g)(h) the last result, difference image and the grid image of the registration.

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, a novel rigid transformation constraint is introduced firstly, which penalizes nonrigid deformations at locations where it is required. The effectiveness of the proposed transform is demonstrated on the 2D synthetic example. a multi-stage vertebrae registration is presented, the effectiveness of this method can be showed on the 2D cervical vertebrae example. From the discussion, this multi-stage vertebra registration is shown to be a feasible way to keep vertebrae bones rigid while performing nonrigid registration.

B. Future Works

In this paper, all the segmentation is processed manually. In actual, the tissue's rigidity can not be got easily. But CT's luminance information shows the bones' rigidity, the bones will be bright and other parts will be dark. CT image can be used to get the tissue's rigidity. The registration using CT and MRI information may get a better result.

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